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VOLUME IV

ADVANCED DURABILITY ANALYSIS
VOLUME IV - EXECUTIVE SUMMARY

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report is Volume IV of a 5-volume final report on the work conducted under AF contract F33615-84-C-3208. The objectives of this program were to: (1) recommend improvements to the current Air Force durability design requirements (i.e., MIL-A-8866B and MIL-A-87221), (2) develop a probabilistic durability analysis method capable of predicting the durability of advanced metallic aircraft structure for functional impairment such as excessive cracking, fuel leakage and ligament breakage, and (3) update the current Air Force Durability Design Handbook (AFWAL-TR-83-3027). Fatigue cracking is the form of degradation considered. This three-phase program consisted of eight tasks. Advanced durability analysis methods were developed and refined under Phase 1. Fatigue test results and fractographic data were acquired and evaluated under Phase 2. Phase 3 was concerned with durability design requirements and suggested improvements, guidelines for implementing the advanced durability analysis and updating the current Air Force Durability Design Handbook (AFWAL-TR-83-3027).

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The advanced durability analysis methods developed under Tasks I - III are reported in Volume I. Analytical methods from Tasks I - III and test results from Task IV are evaluated under Task V and results are reported in Volume II. In Volume III, raw test and fractographic data are presented for Task IV.

This Volume (IV) summarizes the overall results, conclusions and recommendations for the program.

Volume V is a software user's guide for implementing the advanced durability analysis method.

Durability analysis requirements, advanced durability analysis methods, step-by-step procedures and guidelines, and method demonstration are documented in the second edition of the durability design handbook.

FOREWORD

This report was prepared by General Dynamics, Fort Worth Division, under the "Advanced Durability Analysis" program (Air Force Contract F33657-84-C-3208) for the Air Force Wright Aeronautical Laboratories (AFWAL/FIBEC). Margery E. Artley was the Air Force Project Engineer; Dr. John W. Lincoln of ASD/ENFS and James L. Rudd of AFWAL/FIBEC were technical advisors. Dr. S. D. Manning of the General Dynamics' Structures Technology Staff was the program manager and co-principal investigator along with Dr. J. N. Yang of United Analysis Incorporated (Vienna, VA).

Other volumes for this program are as follows:

- Volume I - Analytical Methods
- Volume II - Analytical Predictions, Test Results, and Analytical/Experimental Correlations
- Volume III - Fractographic Test Data
- Volume V - Durability Analysis Software User's Guide

The second edition of the USAF Durability Design Handbook (AFWAL-TR-83-3027) was also developed under this program.

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INTRODUCTION AND SUMMARY

Metallic aircraft structures must be designed to be durable and to resist fatigue cracking in service. Durability "design tools" are needed to analytically ensure that the aircraft structure can be economically maintained with a high degree of operational readiness and warfighting capability. Therefore, a 30-month research program was initiated in 1984 to: (1) develop a probabilistic-based durability analysis method for metallic aircraft structures capable of predicting the functional impairment due to excessive cracking, fuel leakage and/or ligament breakage, (2) recommend improvements to the current Air Force durability design requirements [1,2] and (3) update the current Air Force durability design handbook (AFWAL-TR-83-3027) [3]. This three-phase program included eight tasks. A roadmap for the program is shown in Fig. 1. This is Volume IV of a five-volume sequence of final reports [4-8] for this program.

Under Task I we developed methods for determining the initial fatigue quality or equivalent initial flaw size distribution (EIFSD) for structural details. Methods were developed for estimating and optimizing EIFSD parameters for an "equivalent single hole population" basis. A data pooling procedure was developed including a statistical scaling technique for determining the EIFSD parameters for one or more fractographic data sets in a "global sense." The sensitivity of the EIFSD parameters with respect to key variables (e.g., fractographic crack size range, % bolt load transfer, stress level, load spectrum, etc.) was also investigated.

Task II was concerned with the optimization of current durability analysis methods [9-15] for predicting the probability of crack exceedance, $p(i, \tau)$, for metallic aircraft

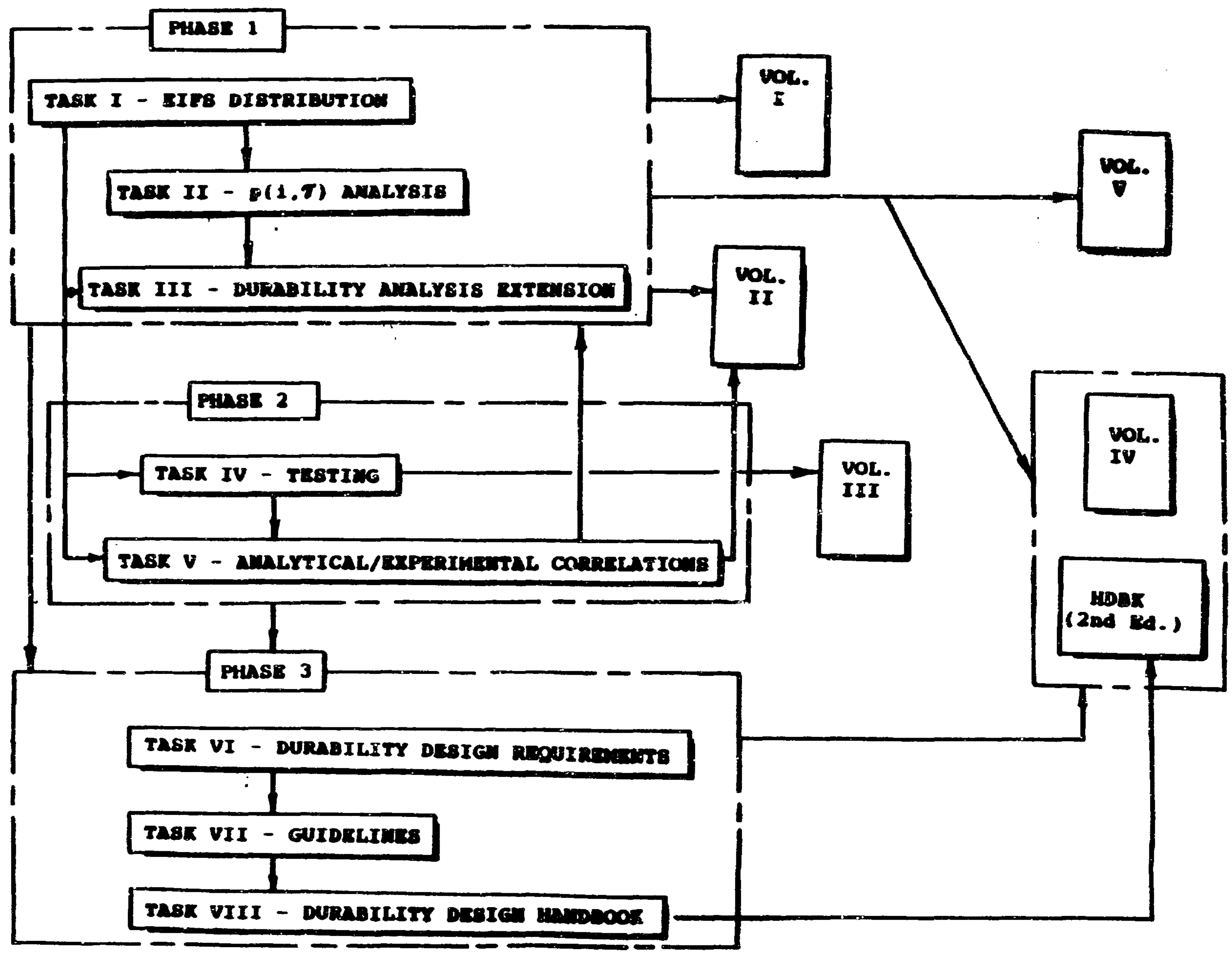


Figure 1. Advanced Durability Analysis Program Roadmap.

structures. Under this task we developed procedures and guidelines for defining suitable service crack growth master curves (SCGMCs) for durability analysis using an analytical crack growth program [e.g., 16,17]. A SCGMC is used to grow the EIFSD forward to predict the probability of crack exceedance at any service time, or the cumulative distribution of service time to reach any crack size. Methods are developed and evaluated for making the SCGMC compatible with the basis on which the EIFSD is established.

In Task III we extended the current durability analysis method [9-15] for the small crack size region to large through-the-thickness cracks (e.g., 0.5"-0.75") associated with functional impairment due to fuel leaks and/or ligament breakage. The recommended approach, referred to as the two-segment deterministic-stochastic approach (DCGA-SCGA), includes the Weibull compatible EIFSD function and deterministic/stochastic crack growth models. Various one-segment and two-segment crack growth approaches (i.e., deterministic and stochastic) were developed and evaluated. Different EIFSD functions (i.e., Weibull compatible, lognormal and two-parameter Weibull) were also considered. The DCGA-SCGA was demonstrated for countersunk and straight-bore fastener holes with clearance-fit fasteners using coupon specimens and full-scale aircraft structure.

Task IV included a two-phase experimental test program with fractographic evaluations. Under Phase I, 31 multi-hole dog-bone specimens were fatigue tested to failure. The phase 2 test program included 105 spectrum fatigue tests using simple dog-bone or double-reversed dog-bone specimens and a strain survey to verify the % bolt load transfer. All specimens tested were 3.00" wide. The material was 7475-T7351 aluminum plate. Both countersunk and straight-bore fastener holes with clearance-fit fasteners were used. None of the fastener holes included any special life enhancement features

such as cold working, interference fit or cold fit bushings. Since no intentional preflaws were implanted in any of the fastener holes, natural fatigue cracks were allowed to initiate and propagate. Fractographic results were acquired for over 180 fatigue cracks.

The experimental results of Task IV were evaluated under Task V. Durability analysis predictions for $p(i, \tau)$ at a given service time and/or cumulative distribution of service time, $F_T(t)$, to reach a given crack size were correlated with results from Task IV. A comprehensive demonstration of the DCGA-SCGA was conducted using coupon specimen results.

Current Air Force durability design requirements [1,2] were reviewed under Task VI. Modifications were proposed to make the requirements more realistic and definitive based on the results of this program.

Guidelines for implementing the advanced durability analysis approach were developed under Task VII. Step-by-step procedures and guidelines were developed for acquiring initial fatigue quality data, for optimizing the EIFSD for durability analysis, for making $p(i, \tau)$ and/or $F_T(t)$ predictions, and for predicting the extent of damage at any service time.

Task VIII was concerned with updating the Air Force Durability Design Handbook [3] to include the advancements made under this program. Advanced durability analysis methods are demonstrated using coupon specimens and the lower wing skins from a fighter aircraft. Methods and guidelines are presented in the second edition of the handbook [18] for implementations.

Software has been developed for implementing the advanced durability analysis methods developed under this program

on an IBM or IBM-compatible PC. The software can be used to: (1) save or screen fractographic data on floppy disk, (2) determine crack growth parameters, (3) optimize EIFSD parameters for Weibull compatible distribution function, (4) predict the crack exceedance probability, $p(i, \tau)$, at any service time or the distribution of service time, $F_T(t)$, to reach any crack size and (5) plot fractographic data and/or durability analysis results.

As shown in Fig. 1, the following final report volumes (AFWAL-TR-86-3017) and handbook (AFWAL-TR-83-3027) document the work conducted under this program:

- Volume I - Analytical Methods
- Volume II - Analytical Predictions, Test Results, and Analytical/Experimental Correlations
- Volume III - Fractographic Test Data
- Volume IV - Executive Summary
- Volume V - Durability Analysis Software User's Guide
- USAF Durability Design Handbook (2nd Edition; AFWAL-TR-83-3027)

SECTION II
DURABILITY ANALYSIS APPROACH

A probabilistic durability analysis approach for metallic aircraft structures is summarized in this section. This approach can be used to analytically predict the probability of functional impairment due to excessive cracking, fuel leaks or ligament breakage. The methodology accounts for the initial fatigue quality variation, crack growth damage accumulation in a population of structural details (e.g., fastener holes, lugs, fillets, cutouts, etc.), load spectra and structural properties. Thus, the extent of damage can be quantitatively estimated at any service time under service conditions. Once the initial fatigue quality or equivalent initial flaw size distribution (EIFSD) has been determined, the probability of functional impairment is obtained by growing the EIFSD forward using a deterministic-stochastic crack growth approach. Essential elements and features of the approach are described in the following and details are given elsewhere [4,5,18].

2.1 INITIAL FATIGUE QUALITY REPRESENTATION

Initial fatigue quality of a structural detail is represented by an equivalent initial flaw size distribution (EIFSD). An equivalent initial flaw (EIFS) is an artificial crack size which results in an actual crack size at an actual point in time when the initial flaw is grown forward. It is determined by back-extrapolating fractographic results and has the following characteristics: (1) an EIFS is an artificial crack assumed to represent the initial fatigue quality of a structural detail in the as-manufactured condition whatever the source of fatigue cracking may be, (2) it has no direct relationship to actual initial flaws in fastener holes such as scratches, burrs, microdefects, etc., and it cannot

be verified by NDI, (3) it has a universal crack shape in which the crack size is measured in the direction of crack propagation, (4) EIFSs are in a fracture mechanics format but they are not subject to such laws or limitations as the "short crack effect," (5) it depends on the fractographic data used, the fractographic crack size range used for the back-extrapolation and the crack growth rate model used, (6) it must be grown forward in a manner consistent with the basis for the EIFS, and (7) EIFSs are not unique - a different set is obtained for each crack growth law used for the back-extrapolation.

Each structural detail to be considered in the durability analysis is assumed to have a single dominant initial flaw. An EIFS is a statistical variable which describes the population of equivalent intial flaw size at time zero.

An EIFS is not strictly "generic" because it depends on the following: (1) crack growth rate model used to back-extrapolate fractographic results, (2) conditions reflected in the fractographic results (e.g., material, type fastener/hole/fit, load spectra, etc.), (3) fractographic crack size range used (i.e., AL-AU), and (4) goodness-of-fit criterion. However, the real issue is not whether the EIFSs or EIFSD is generic or not. The important question is: "Can an EIFSD, based on the fractographic results for one or more data sets, be used to make reasonable durability analysis predictions for a different set of conditions, e.g., similar material, same type of load spectra, e.g., fighter, bomber or transport, similar type fastener/hole/fit but different stress levels and/or % bolt load transfers?" The answer to this question is "yes"! We have demonstrated under this program that an EIFSD does not have to be "generic" to obtain reasonable durability analysis predictions for functional impairment.

There are many facets involved in estimating the initial fatigue quality (IFQ) of structural details. Essential elements for determining IFQ are: (1) suitable fractographic data acquired for "natural fatigue cracks" (i.e., no intentional pre-flaws) in the type of structural detail to be included in the durability analysis, (2) a physically-meaningful EIFSD function for representing IFQ and (3) a method for estimating the EIFSD parameters using a data pooling procedure. Once the EIFSD parameters have been estimated, the candidate EIFSD is then evaluated and justified for desired durability analysis applications.

An EIFS value for a fastener hole is determined by back-extrapolating fractographic data in a selected crack size range, AL-AU, using a simple but versatile deterministic crack growth rate model proposed by Yang and Manning [10,19]. Thus, EIFS data sets are obtained from available fractographic data sets. Then, these EIFS data sets are used to determine the EIFS distribution parameters. Essential elements for estimating the EIFSD parameters, including the statistical scaling and data pooling procedures to account for fractographic data sets with different numbers of fastener holes per specimen, are described in Vols. I and II.

Software is available in Volume V [8] for saving and retrieving fractographic data, estimating the EIFSD parameters and evaluating the candidate EIFSD for durability analysis. A plotting capability is available for displaying results. This software is further described in Section VI of this Volume (IV).

2.2 TWO-SEGMENT DETERMINISTIC-STOCHASTIC CRACK GROWTH APPROACH

Once the EIFS distribution has been determined, the entire population of equivalent initial flaws can be grown for-

ward for durability analysis. In this regard, a two-segment deterministic-stochastic crack growth approach, DCGA-SCGA, described in Fig. 2, is recommended. This method can be used to grow the EIFSD to predict the probability of functional impairment due to excessive cracking, fuel leaks or ligament breakage. Various other crack growth approaches were also developed [4] and evaluated [5] under this program.

Durability analysis is primarily concerned with predictions for the following quantities: (1) The probability that a given crack size x_1 in the ith stress region (i = 1,2,...) will be exceeded at any service time τ, referred to as the crack exceedance probability $p(i,\tau)$, and (2) the cumulative distribution of service time $F_T(t)$ to reach any crack size x_1 in the ith stress region (i = 1,2,...). Conceptual plots for $p(i,\tau)$ and $F_T(t)$ are shown in Fig. 3. Then, the "extent of damage" for the entire durability component due to excessive cracking, fuel leaks and/or ligament breakage can be determined using $p(i,\tau)$ predictions for given stress regions of the structure and the Binomial statistics.

The DCGA-SCGA is described in detail in Volume I [4]. Only the essentials are described in this section; see Fig. 2.

When the crack size is equal to or smaller than a reference crack size a_0, a deterministic crack growth rate model is used to grow the EIFSD forward to predict the crack exceedance probability, $p(i,\tau)$. The reference crack size a_0 is chosen to be the upper limit AU of the fractographic data range used to determine EIFSD. When the crack size is larger than a_0, however, a stochastic crack growth rate model proposed by Yang, et al [e.g., 20,22,23,29], is used to account for the crack growth variability in service.

The crack growth rate parameters in both crack size re-

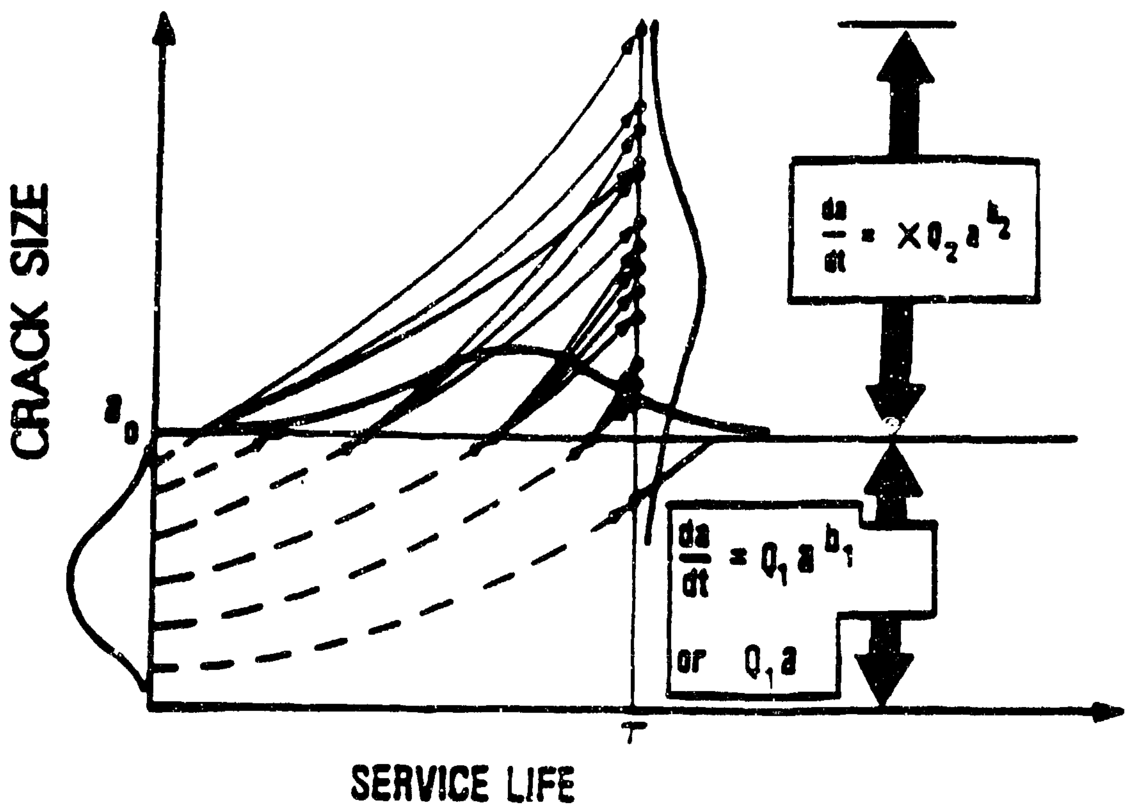
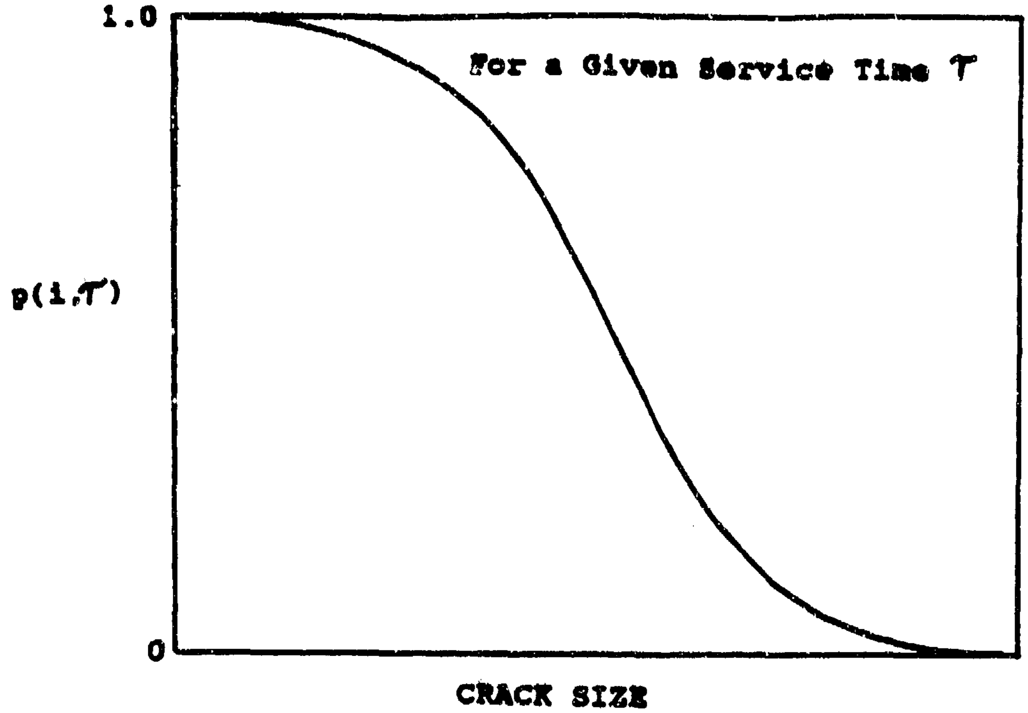
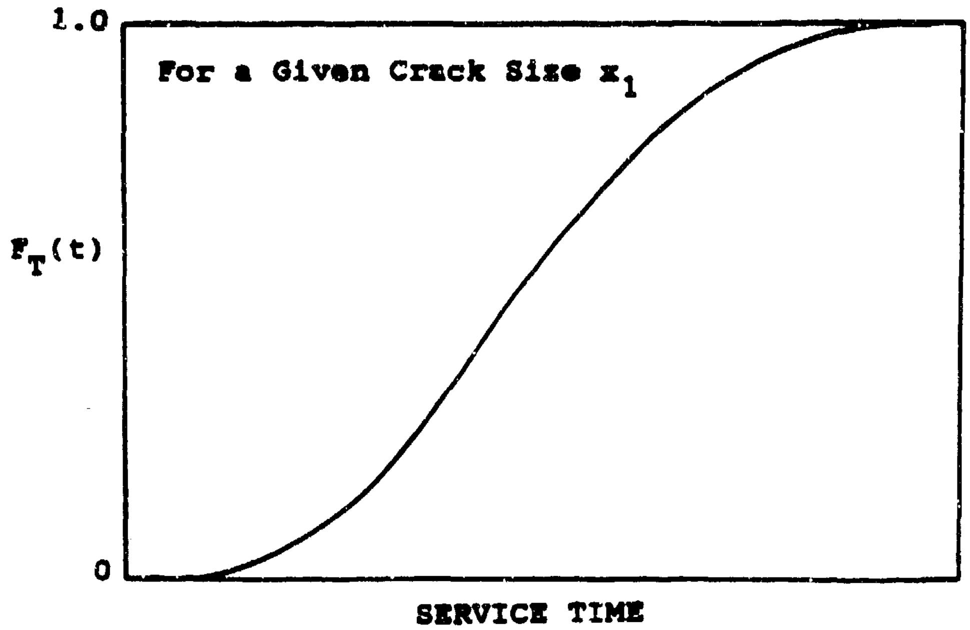


Figure 2. Two-Segment Deterministic-Stochastic Crack Growth Approach (DCGA-SCGA).



(a) Probability of Crack Exceedance at Any Given Service Time τ



(b) Cumulative Distribution of Service Time to Reach any Given Crack Size x_1

Figure 3. Durability Analysis Predictions: (a) Probability of Crack Exceedance at Any Given Service Time τ and (b) Cumulative Distribution of Service Time to Reach Any Given Crack Size x_1.

ons described above can be estimated using suitable fractographic data, if available, or an analytical crack growth program [e.g., 6]. If an analytical crack growth program is used, it must first be "tuned" or curve fitted in the small crack size region (e.g., AL-AU = 0.01" - 0.05") to the same basis as the EIFSD. Procedures and guidelines for determining a service crack growth master curve (SCGMC) using an analytical crack growth program are given elsewhere [18]. A SCGMC can be determined using linear elastic fracture mechanics principles without violating "short crack" fracture mechanics limitations.

Functional impairment occurs when a limiting crack size, x_1 is exceeded. For example, in the case of fastener holes the following limiting crack sizes could be used: (1) for excessive cracking; x_1 = 0.03" - 0.05" (economical repair limit for fastener holes), for fuel leaks; x_1 = size of through-the-thickness crack, and (3) for ligament breakage; x_1 = hole-to-hole dimension between adjacent fasteners. Given the limiting crack size x_1 for functional impairment, the probability of functional impairment for any stress region at any service time, t, due to excessive cracking, fuel leakage or ligament breakage can be obtained from the predicted crack exceedance probability $p(i, \tau)$. Then, the Binomial distribution is used to predict the probability of functional impairment at any service time, τ, for the entire aircraft structure as described in detail in Vol. II [5].

SECTION III

EXPERIMENTAL PROGRAM, RESULTS AND CONCLUSIONS

An experimental program was conducted to evaluate, refine and verify the advanced durability analysis methodology for metallic aircraft structures for both small (e.g., <0.05") and large (e.g., 0.50"-0.75") through-the-thickness fatigue cracks. The experimental program and conclusions are summarized in this section. Test results are evaluated in Volume II [5]. Complete test results and fractographic data are documented in Volume III [6].

3.1 EXPERIMENTAL TEST PROGRAM

The test matrix is shown in Table 1 and specimen details are shown in Figs. 4-6. All tests were conducted in lab air using dog-bone type specimens manufactured from 7475-T7351 aluminum plate (t = 0.50"). Fastener holes were drilled using typical production methods without any special life enhancement conditioning (e.g., coldworking, interference fit, etc). Both straight-bore and countersunk fastener holes were considered.

All specimens were fatigue tested to failure using a selected load spectrum (i.e., F-16 400 hr., F-16C/D or B-1) and a maximum stress level. Fractographic results were acquired for the largest fatigue crack in one or more fastener holes per specimen. Test specimens with three countersunk fasteners (Fig. 4) were used to acquire data for verifying statistical scaling. A strain survey was also performed using the double-reverse dog-bone specimen design shown in Fig. 6. The strain survey was conducted to evaluate the percentage of bolt load transfer as a function of the total applied load.

3.2 EXPERIMENTAL RESULTS

Fractographic data (i.e., crack size versus flight hours) were acquired for fatigue cracks. The raw fractographic data, time-to-failure results, applicable testing and specimen details are given in Volume III [6]. A typical fractographic data plot is shown in Fig. 7 for the WWPF data set.

The following fatigue crack initiation trends were observed: (1) no load transfer specimens (with or without a bolt in the hole) - cracks typically initiated in the bore of the fastener hole, and (2) bolt load transfer specimens - corner cracks generally initiated in the hole at the interface of the mating dog-bone halves. The fatigue crack initiation origins and trends observed in this program for both straight bore and countersunk fastener holes are very similar

Table 1. Experimental Test Matrix.

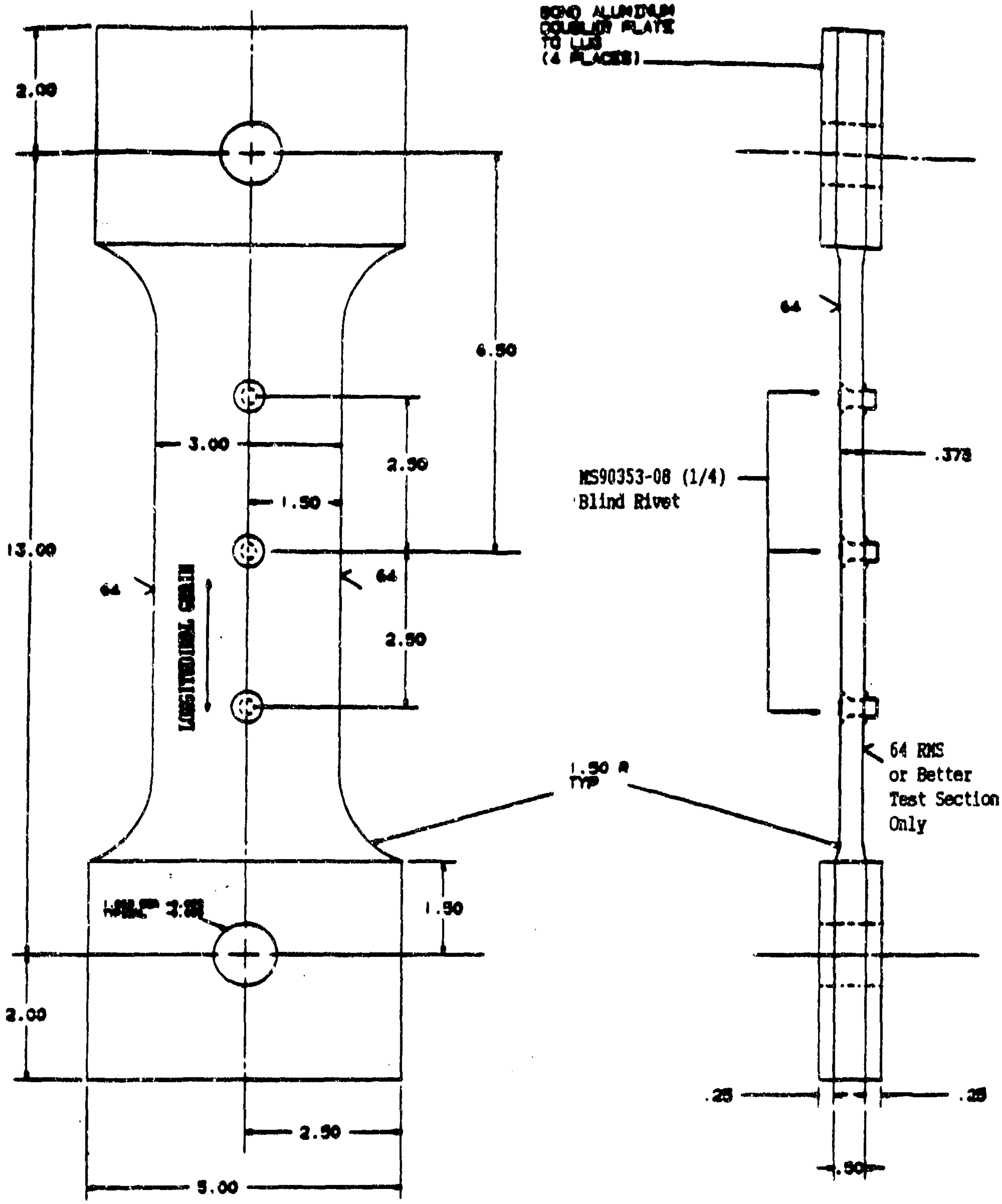
Data Set	Test Phase	Test Series	No. Spec. Tested	Max. Stress (ksi)	% LT	Load Spectrum	Material	(1) Type Hole	(2) Fastener	Ref. Fig.
WQFI	1	I(a)	15	34	0	F-16 400 Hr.	7475-T7351	CSK	MS 90353-08	4
WBI	1	I(b)	16	36	0	B-1	↓	CSK	MS 90353-08	4
[illegible]	2	IV(a)	13*	34	0	F-16 400 Hr.	↓	SB	NAS 6204-08	5
WWFB	2	IV(b)	12*	34	0	B-1	↓	SB	NAS 6204-08	5
WWFCL	2	IV(c)	5	34	0	F-16 C/D	↓	SB	NAS 6204-08	5
WWFCH	2	IV(c)	8	40.8	0	F-16 C/D	↓	SB	NAS 6204-08	5
WWFFO	2	IV(h)	15	34	0	F-16 400 Hr.	↓	SB	(open hole)	5
[illegible]	2	IV(d)	15	36	15	F-16 400 Hr.	↓	CSK	MS 90353-08	6
[illegible]	2	IV(e)	15	40.8	15	F-16 400 Hr.	↓	CSK	MS 90353-08	6
WBNFB	2	IV(f)	15	34	15	B-1	↓	CSK	MS 90353-08	6
WABNSBM4	2	IV(g)	15	40.8	15	B-1	↓	CSK	MS 90353-08	6

Notes:

* Including 4 specimens tested under General Dynamics sponsored research

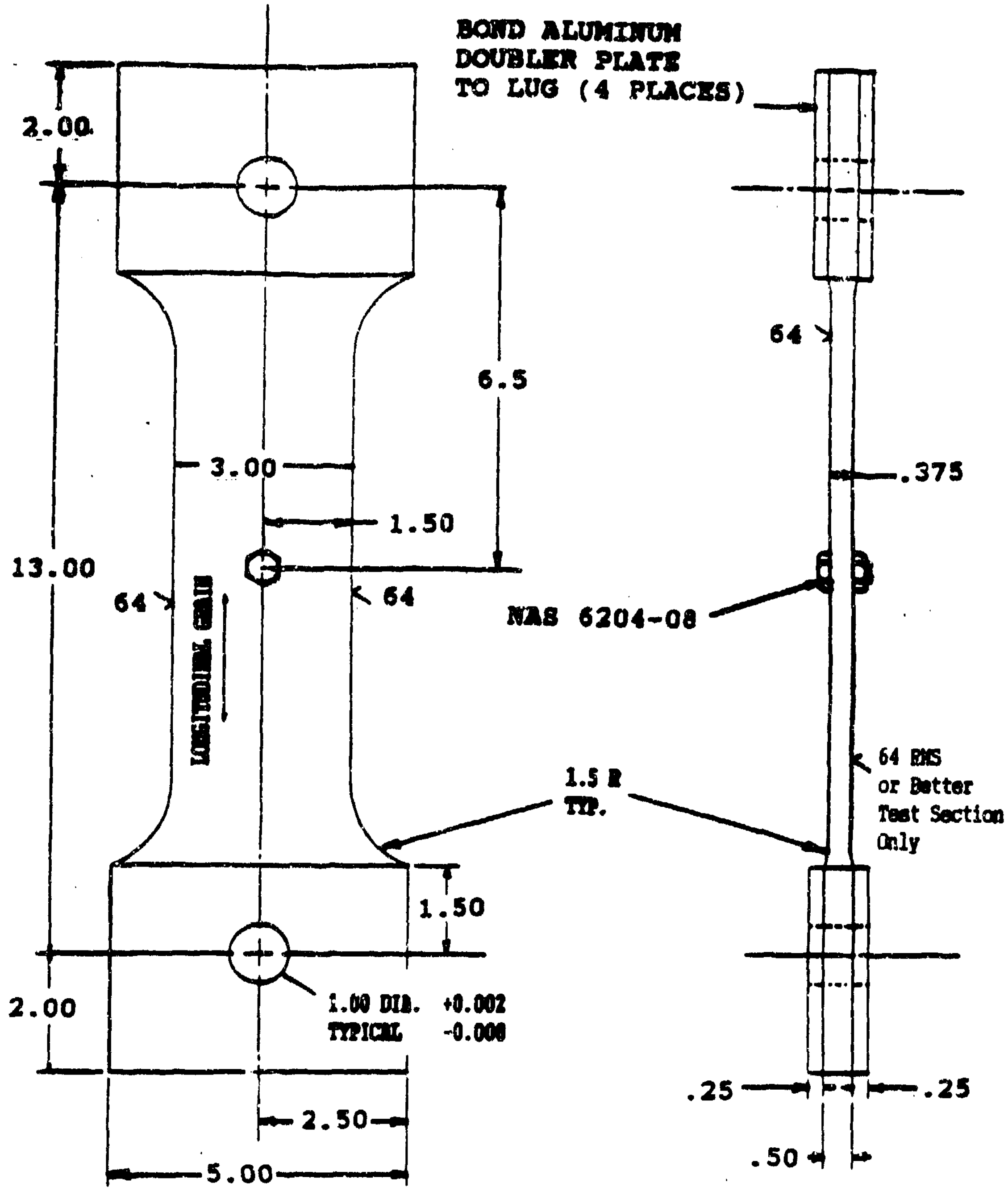
(1) CSK = Countersunk; SB = Straight Bore

(2) NAS 6204-08 (1/4" Dia.) protruding head bolt (steel)
MS 90353-08 (1/4" Dia.) blind, pull-through rivet



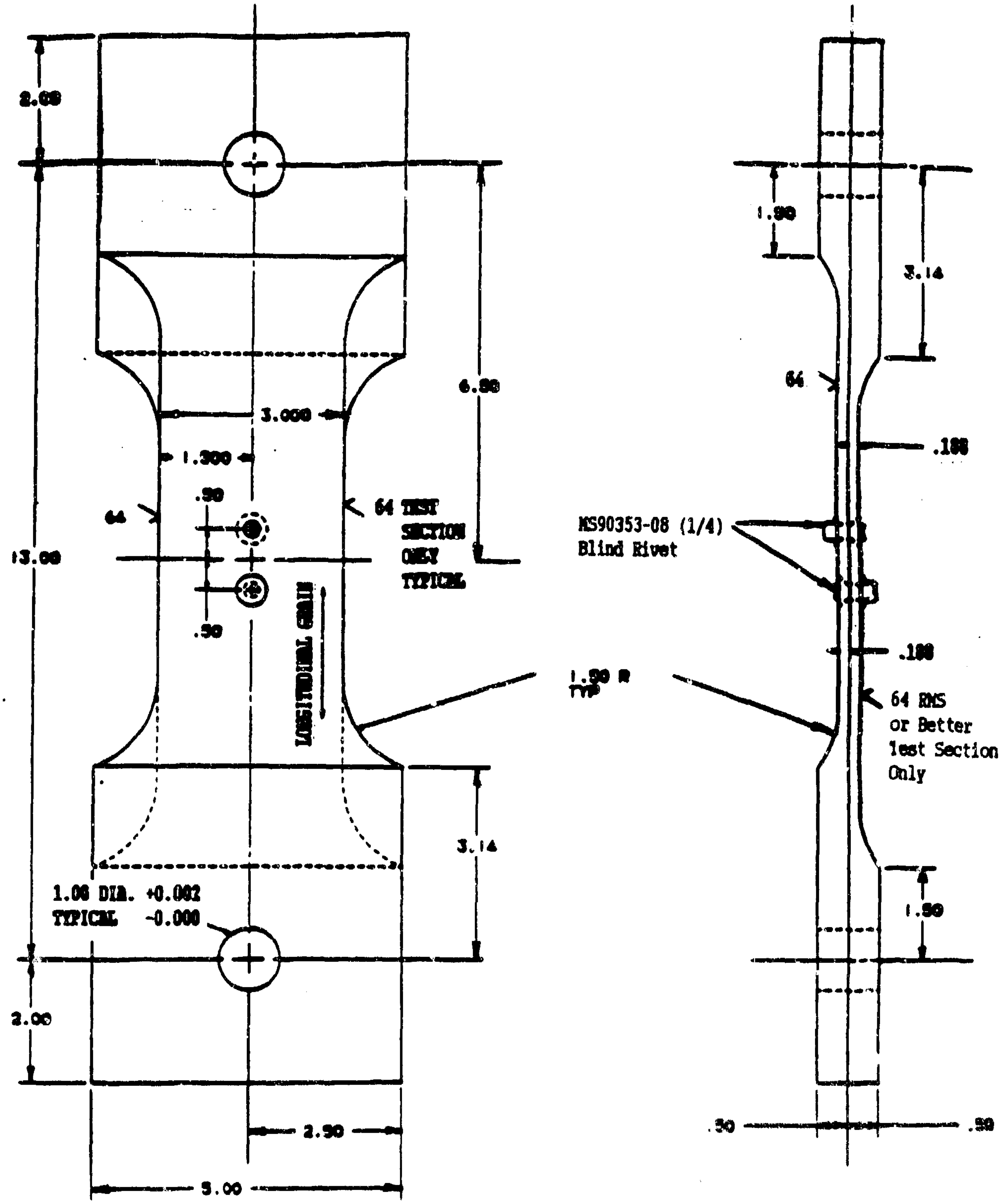
NOTES: 1. MATERIAL: 7475-T7351 ALUMINUM PLATE (1/2" STOCK)
2. MATCH DRILL HOLES USING MODIFIED WINSLOW SPACEMATIC DRILL (NO DEBURRING)
3. DRILL AND INSTALL MS90353-08 RIVETS PER M198
4. ALL DIMENSIONS IN INCHES

Figure 4. Design Details for WFI Data Set Specimens.



NOTES: 1. MATERIAL: 7475-T7351 ALUMINUM PLATE (1/2" STOCK)
2. DRILL HOLES USING MODIFIED WINSLOW SPACEMATIC (NO DEBURRING)
3. DRILL AND INSTALL NAS 6204-08 BOLT PER M198
4. ALL DIMENSIONS IN INCHES

Figure 5. Dog-Bone Specimen with Single Hole.



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3. DRILL AND INSTALL MS90353-08 RIVETS PER E198
4. ALL DIMENSIONS IN INCHES

Figure 6. Double-Reversed Dog-Bone Specimen (15% Load Transfer).

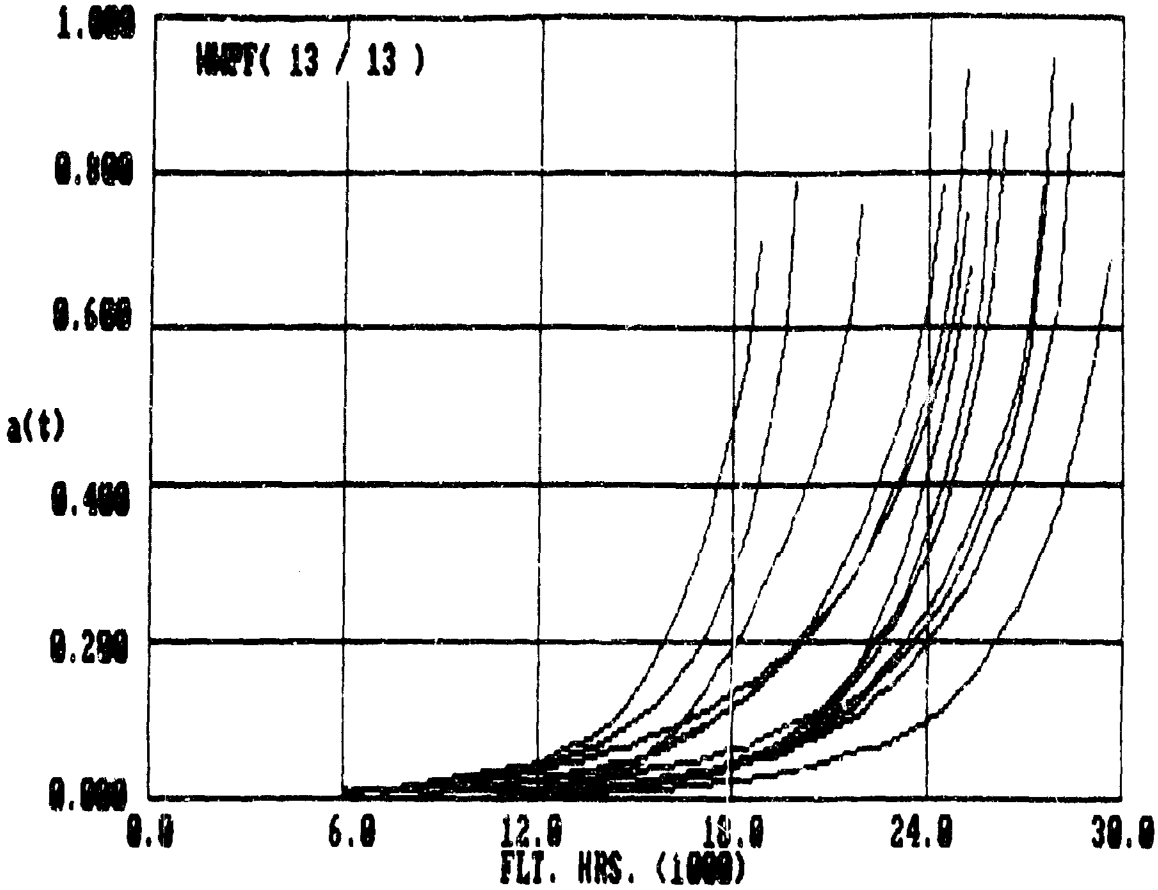


Figure 7. a(t) Versus t Fractographic Data for WWPF Data Set (Full Range).

to those in the "Fastener Hole Quality" program [24] and the "Durability Methods Development" program [25].

Strain survey results, based on the specimen type shown in Fig. 6, are shown in Fig. 8. Strain gage locations and specimen freebodies are shown in Fig. 9.

Considerably larger scatter in the fatigue test results was observed for countersunk fastener holes than for straight-bore fastener holes. The clearance fit and drilling procedure/quality for both types of fastener holes were comparable. This strongly suggests that a larger initial flaw size should be used for the durability analysis of countersunk fastener holes than for straight-bore fastener holes.

3.3 CONCLUSIONS

Experimental results are evaluated in detail in Volume II [5], including conclusions, recommendations and guidelines for acquiring initial fatigue quality data. Overall conclusions for the experimental test program are summarized below.

1. The experimental results acquired under this program were useful for: (1) investigating/evaluating the IFQ of clearance-fit fastener holes, (2) evaluating, refining and demonstrating the durability analysis methodology, including statistical scaling technique, described in Volume I [4], (3) estimating the % bolt load transfer of double-reversed dog-bone specimens, and (4) conducting various durability-related studies.

2. Experimental procedures and guidelines have been developed for acquiring IFQ data for fastener holes. Details are given in Volume II [5]. The cleanest way to acquire IFQ data for fastener holes is to fatigue test specimens with a single fastener hole to failure. Three types of test specimens are recommended for acquiring IFQ data as shown in Fig. 10.

3. Fractographic data should be surveyed and censored before being used to estimate the IFQ or EIFSD or any other durability analysis purpose. Data screening is needed to determine the quality and character of the data and to reject suspicious data. Questionable fractographic data should be censored from the data set. Computer software is available in Volume V [8] for plotting and screening the fractographic data.

4. A strain survey was conducted using a double-reversed dog-bone type specimen (Fig. 6) with a "15% bolt load transfer design." It was found that the actual percentage of bolt load transfer was approximately 7% at 100% applied specimen load. Also, the amount of bolt load transfer varied as a function of the applied load and fastener-hole fit.

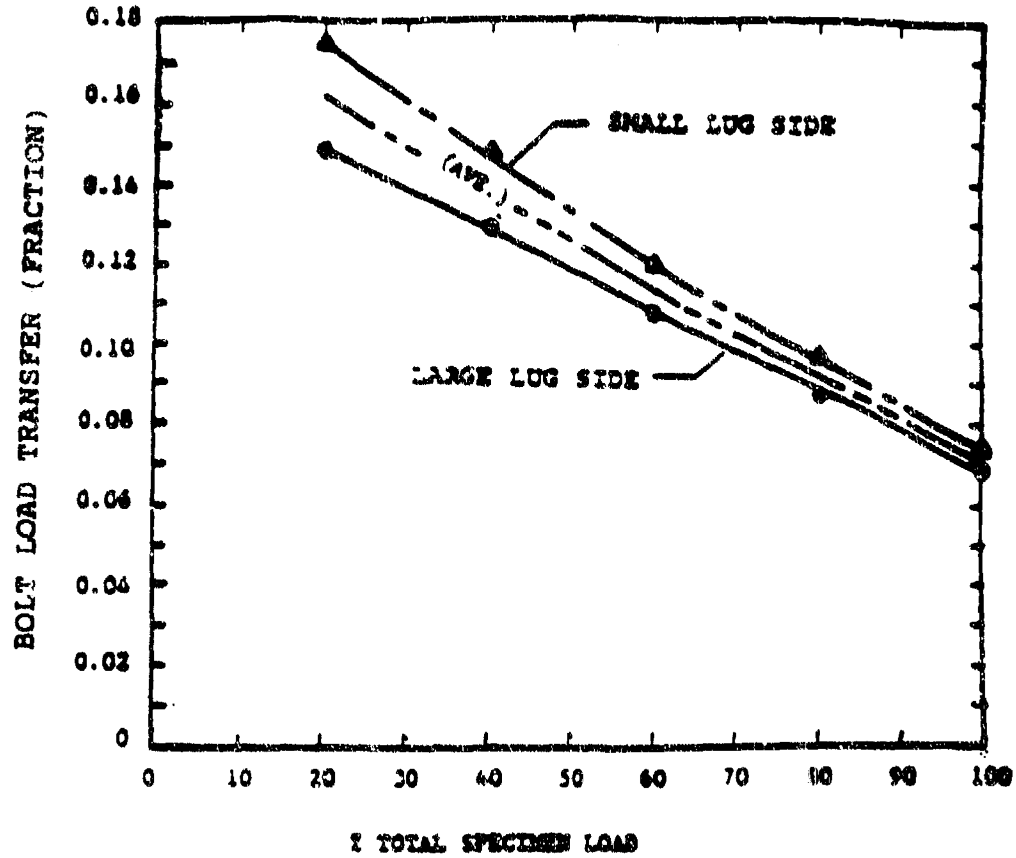


Figure 8. Bolt Load Transfer (Fraction) Versus Specimen % Load.

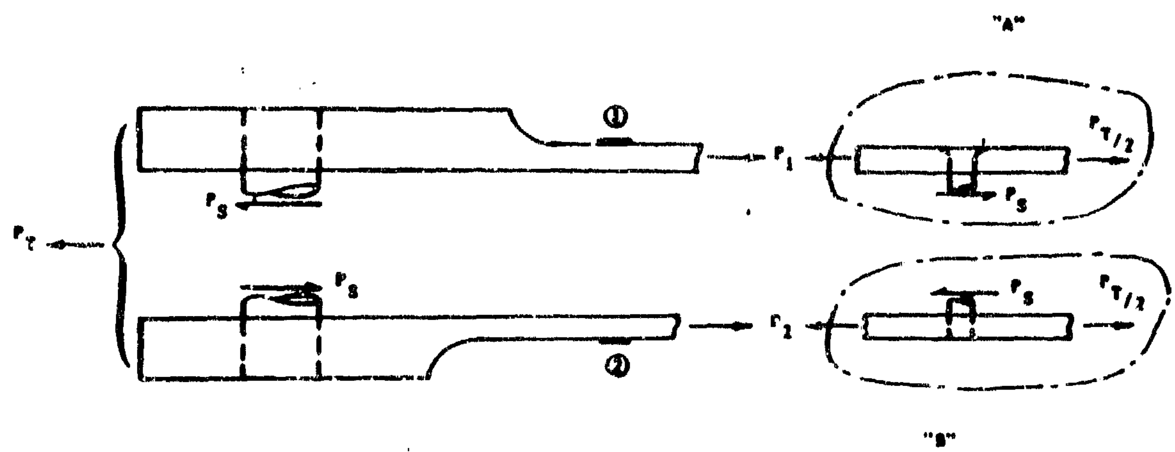
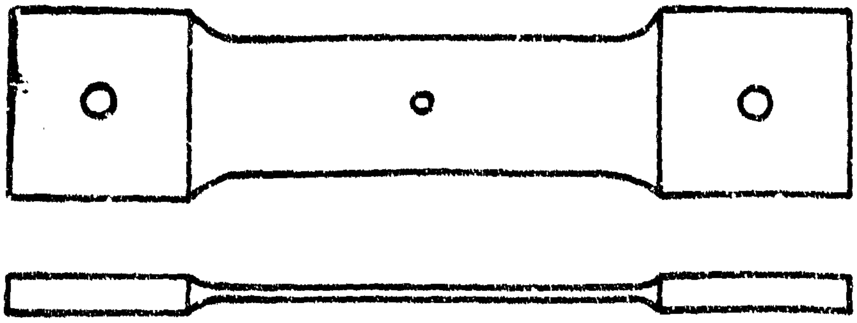
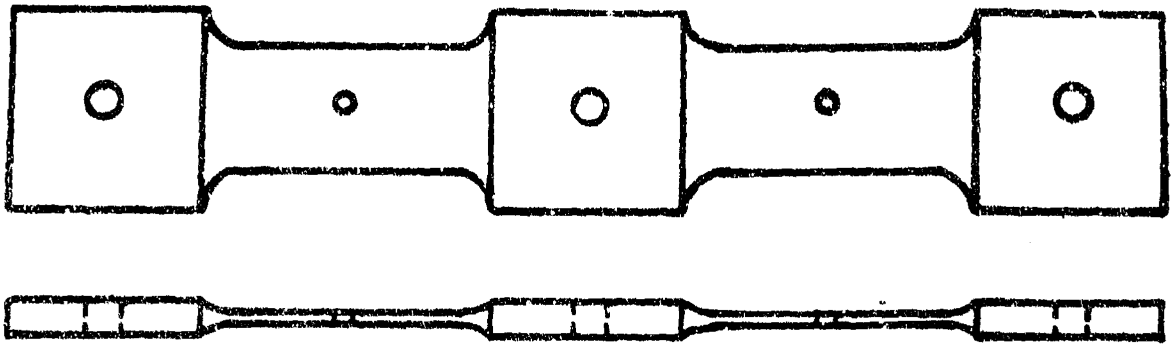


Figure 9. Freebodies for Double-Reversed Dog-Bone Type Specimen.

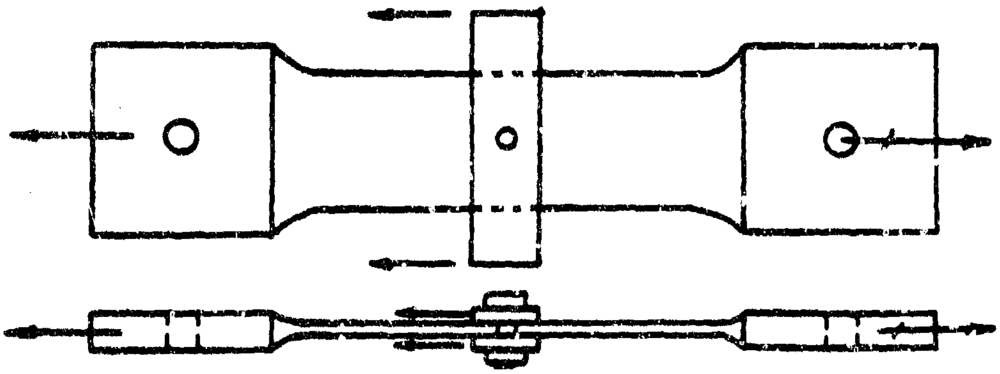


(a) No Bolt Load Transfer Dog-Bone Specimen



(b) Two-For-One No-Bolt Load Transfer Dog-Bone Specimen

(Use double or single shear configuration)



(c) Dog-Bone Specimen With Bolt Load Transfer

Figure 10. Recommended Specimen Types for Acquiring IFQ Data for Fastener Holes.

5. Only straight shank and countersunk clearance-fit fasteners in 7475-T7351 aluminum were investigated under this program. The effect of interference fit fasteners and cold-working on the IFQ of fastener holes remains to be investigated.

SECTION IV

DEMONSTRATION OF DURABILITY ANALYSIS METHODS

The comprehensive advanced durability analysis demonstration, documented in Volume II [5] and the second edition of the durability design handbook [18], is summarized in this section. Durability analysis methods for predicting the crack exceedance probability, $p(i, \tau)$, and the cumulative distribution of service time to reach any crack size, $F_T(t)$, are demonstrated using: (1) coupon specimen results, and (2) tear-down inspection results for the F-16 lower wing skins.

4.1 DEMONSTRATION FOR DOG-BONE SPECIMENS

The advanced durability analysis method described in Section II is demonstrated for both countersunk and straight-bore fastener holes in the following. The initial fatigue quality is established based on fractographic results obtained using narrow specimens. Then, predictions for the crack exceedance probability, $p(i, \tau)$, and cumulative distribution of service time to reach a specific crack size, $F_T(t)$, in the large crack size region are made using the DCGA-SCGA. Predictions are correlated with actual fractographic results obtained using wide dog-bone specimens.

4.1.1 Countersunk Fastener Holes

Three base-line fractographic data sets (i.e., "AFXLR4", "AFXMR4" and "AFXHR4") based on 1.5" wide specimens are used to determine the initial fatigue quality. The three data sets are described in Table 2 and specimen details are shown in Fig. 11. Fractographic results for each data set were plotted and screened for abnormal behavior and data sparsity. As a result of this screening process, one crack (#8) was deleted from the AFXLR4 data set.

The Weibull compatible distribution is used to represent the distribution of EIFS. Using these three base-line fractographic data sets in the crack size range of AL-AU = 0.01"

Table 2. Description of Fractographic Data Sets Used to Determine the IFQ for Countersunk Fastener Holes.

DATA SET (Ref. 25)	SPECIMENS USED (4)	σ (3) (ksi)	% LT	H (In.)	t (In.)	FASTENER (2)	LOAD SPECTRUM
AFXLR4	10/11 (5)	32	15	1.5	.1875	MS90353-08	F-16 400 HR
AFXMR4	9/9	34					
AFXHR4	10/10	38					

Notes: (1) Material: 7475-T7351 aluminum
(2) Blind pull-through rivet (countersunk head)
(3) Gross section stress
(4) xx/yy = No. of specimens used/total no. of specimens in data set
(5) Deleted crack no. 8 from data set

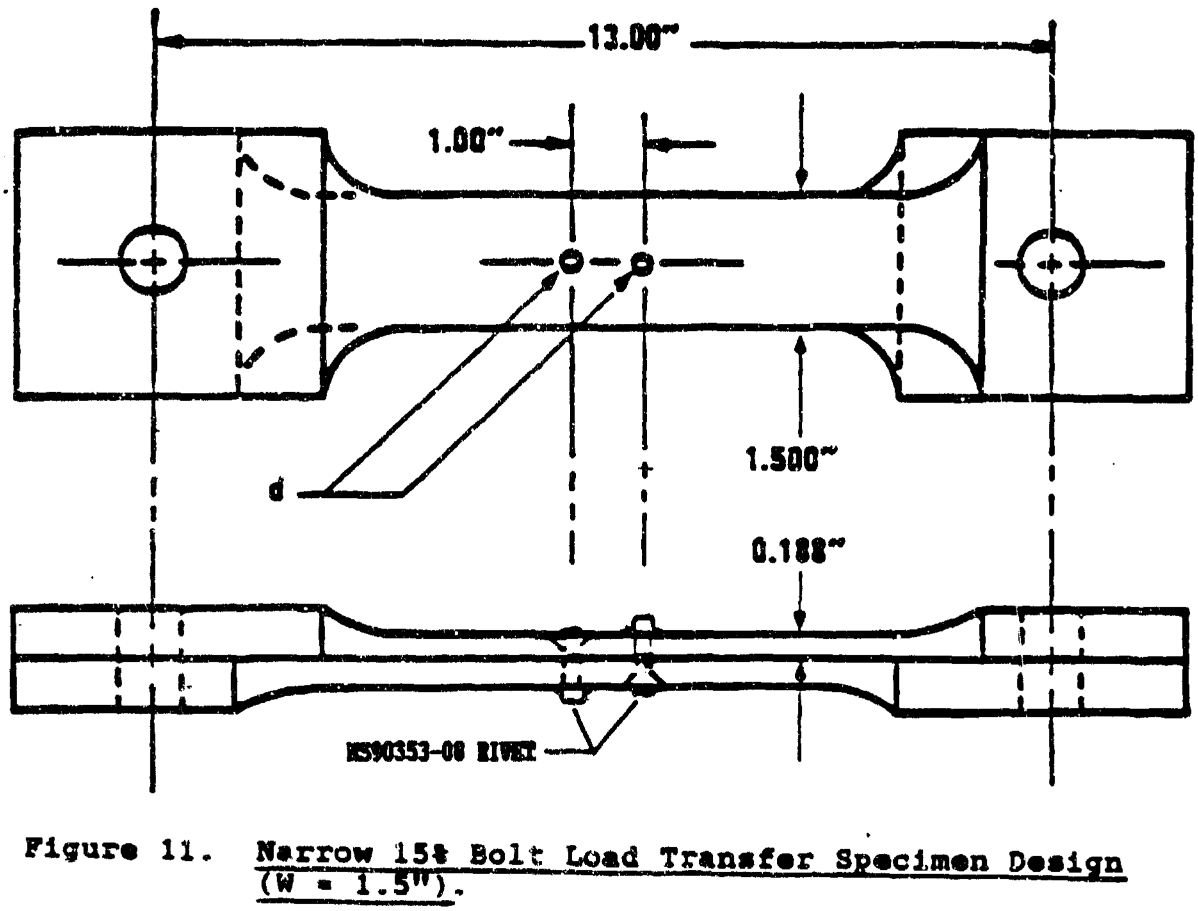


Figure 11. Narrow 15% Bolt Load Transfer Specimen Design (W = 1.5").

- 0.05", as well as data pooling and statistical scaling procedures, the following EIFS distribution parameters were estimated: x_u = 0.03", α = 1.716 and ϕ = 6.308. The scaling factor for countersunk specimens is ℓ = 4, since each specimen is made of two pieces of aluminum with two fastener holes. The established EIFSD is grown forward to predict the crack exceedance probability, $p(i,\tau)$, and cumulative distribution of service time to reach any given crack size, $F_T(t)$, for WAFXMR4 and WAFXHR4 data sets. The two-segment DCGA-SCGA approach described in Section II has been used.

Fractographic data for WAFXMR4 and WAFXHR4 were generated using the same dog-bone specimen shown in Fig. 11 except that the specimen has a 3.00" width. Thus, fractographic data in the large crack size range can be obtained from these wide specimens. The description of WAFXMR4 and WAFXHR4 data sets is described in Table 3.

The predicted probability of crack exceedance at τ = 11,608 flight hours for WAFXMR4 is displayed in Fig. 12 as a solid curve. Also shown in this figure as solid circles are the actual test data for comparison. Further, the predicted probability of crack exceedance at τ = 7,000 flight hours for WAFXHR4 is shown in Fig. 13 as a solid curve and the solid circles denote the actual fractographic test results.

The predicted cumulative distribution of service time to reach a crack size of 0.73" for WAFXMR4 is displayed in Fig. 14 as a solid curve. The actual fractographic results are shown in the same figure as solid circles for comparison. Similarly, the prediction for the cumulative distribution of service time to reach a crack size of 0.59" for WAFXHR4 is shown in Fig. 15 as a solid curve. The solid circles depicted in the same figure are the actual fractographic test data for comparison. It is observed from Figs. 12 to 15 that the correlations for countersunk fastener holes between the ex-

Table 3. Description of WAFXMR4 and WAFXHR4 Fractographic Data Sets.

DATA SET	% LOAD TRANSFER	NO. CRACKS	GROSS STRESS (KSI)	WIDTH (In.)
WAFXMR4	15	14	34	3.0
WAFXHR4	15	13	40.6	3.0

Notes: 1. 7475-T7351 Aluminum
2. Ref. Fig. 6 for specimen design details.

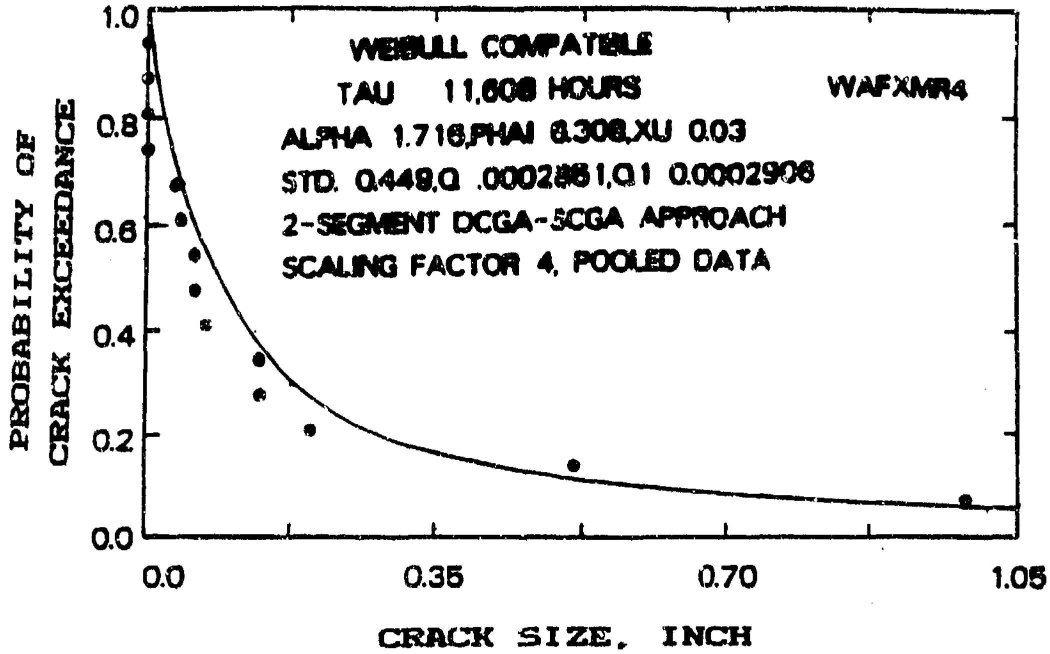


Figure 12. Correlation Between Predicted Crack Exceedance Probability at τ = 11608 Flight Hours for WAFXMR4 Data Set and Actual Fractographic Results.

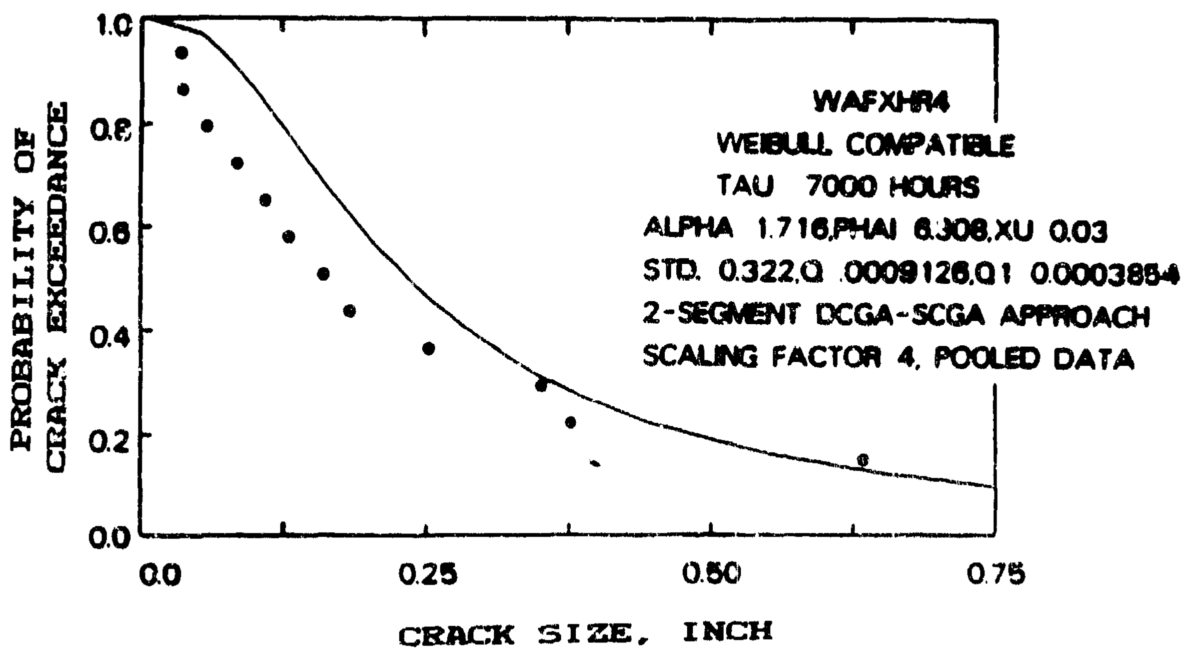


Figure 13. Correlation Between Predicted Crack Exceedance Probability at τ = 7000 Flight Hours for WAFXHR4 Data Set and Actual Fractographic Results.

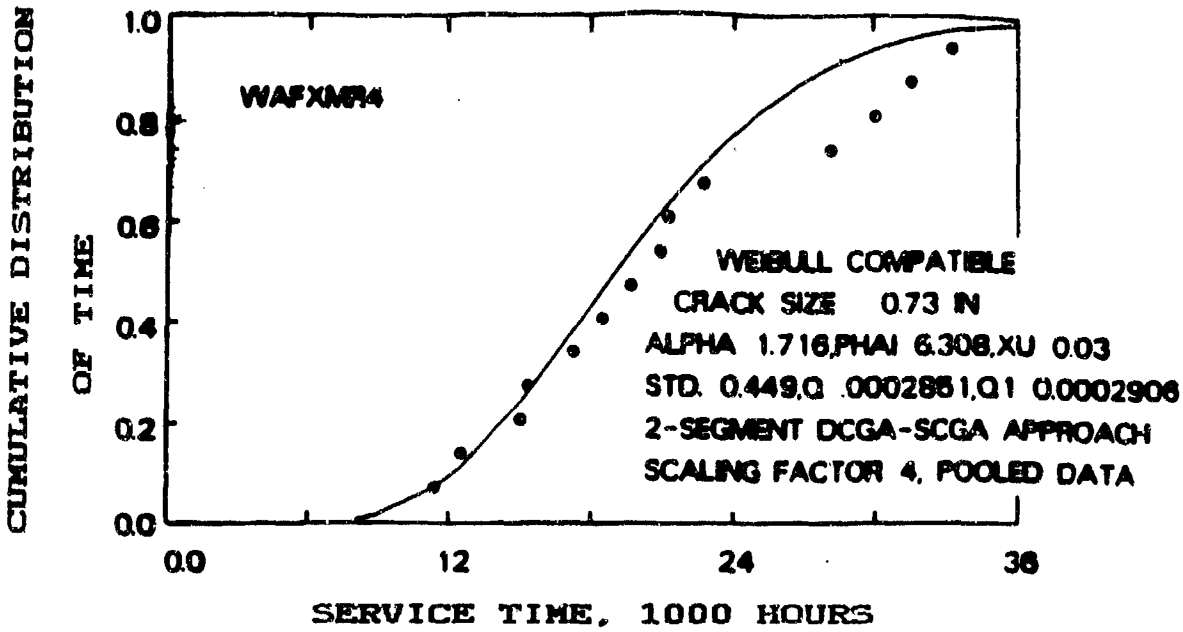


Figure 14. <u>Correlation Between Predicted Distribution of Service Time to Reach 0.73" Crack Size for WAFXMR4 Data Set and Actual Fractographic Results.</u>

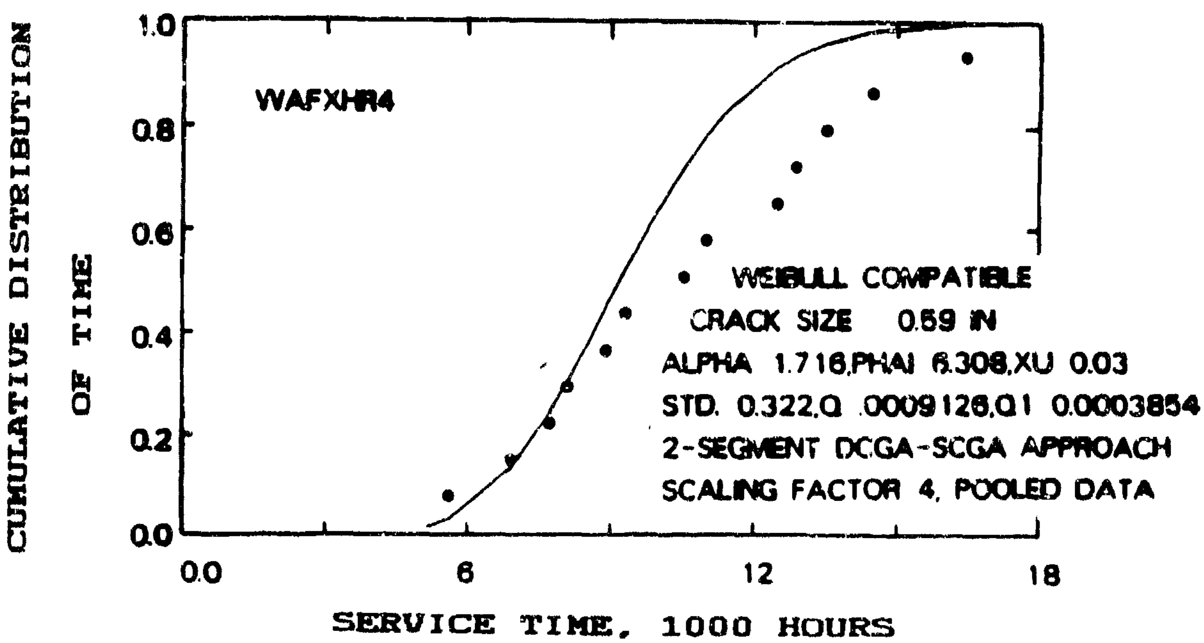


Figure 15. <u>Correlation Between Predicted Distribution of Service Time to Reach 0.59" Crack Size for WAFXHR4 Data Set and Actual Fractographic Results.</u>

perimental results and the durability anal . predictions are very reasonable.

4.1.2 Straight-bore Fastener Holes

The durability analysis demonstration for straight-bore fastener holes was conducted as follows. Two fractographic data sets (i.e., "WPF" and "XWPF") [24] were used to determine the IFQ of straight-bore, clearance-fit, fastener holes in 7475-T7351 aluminum. The two data sets are described in Table 4. Specimen details for the WPF and XWPF data sets are shown in Figs. 16 and 17, respectively. Fractographic results for each data set were screened by surveying the fractographic data plots. Two abnormal fatigue cracks were deleted from each data set for purposes of defining the IFQ.

Fractographic data for each censored data set in the crack size range AL-AU = 0.01" - 0.05" were used to determine the crack growth rate parameter. Computer software filename = "QSZAT" from Volume V [8] was used. The Weibull compatible distribution is used to represent the distribution of EIFS. There is only one fastener hole and one piece of aluminum per WPF specimen, whereas there are two fastener holes with two pieces of aluminum per XWPF specimen. Hence, the scaling factor for WPF data set is $\ell = 1$ and that for XWPF data set is $\ell = 4$. Using the data pooling and statistical scaling procedures, EIFSD parameters were estimated based on the WPF and XWPF data sets pooled together. Computer program filename = "WCIFQ" described in Vol. V [8] was used; with the results $x_u = 0.03"$, $\alpha = 4.782$ and $\phi = 4.658$.

With the EIFSD parameters determined above from pooled base-line data (i.e., WPF and XWPF data sets), the EIFS population was grown forward to conduct durability analysis predictions using DCGA-SCGA described in Section II. Specifically, predictions for crack exceedance probability, $p(i, \tau)$, and the cumulative distribution of service time to reach any

Table 4. Description of Fractographic Data Sets Used to Determine the IFQ for Straight-Bore Fastener Holes.

Data Set (1)	No. of Specimens Used	(4) (KSI)	% LT	W (In.)	Fastener	Load Spectrum
WPF (5)	31/33 (2)	34	0	1.5	NAS6204-8	F-16 400 HR
XWPF	31/33 (3)	34	15	1.5	↓	↓

Notes:

(1) 7475-T7351 Aluminum
(2) Deleted fatigue cracks #2 and 6
(3) Deleted fatigue cracks #11 and 16
(4) Gross section stress for peak spectrum load
(5) Ref. FHQ program [24]

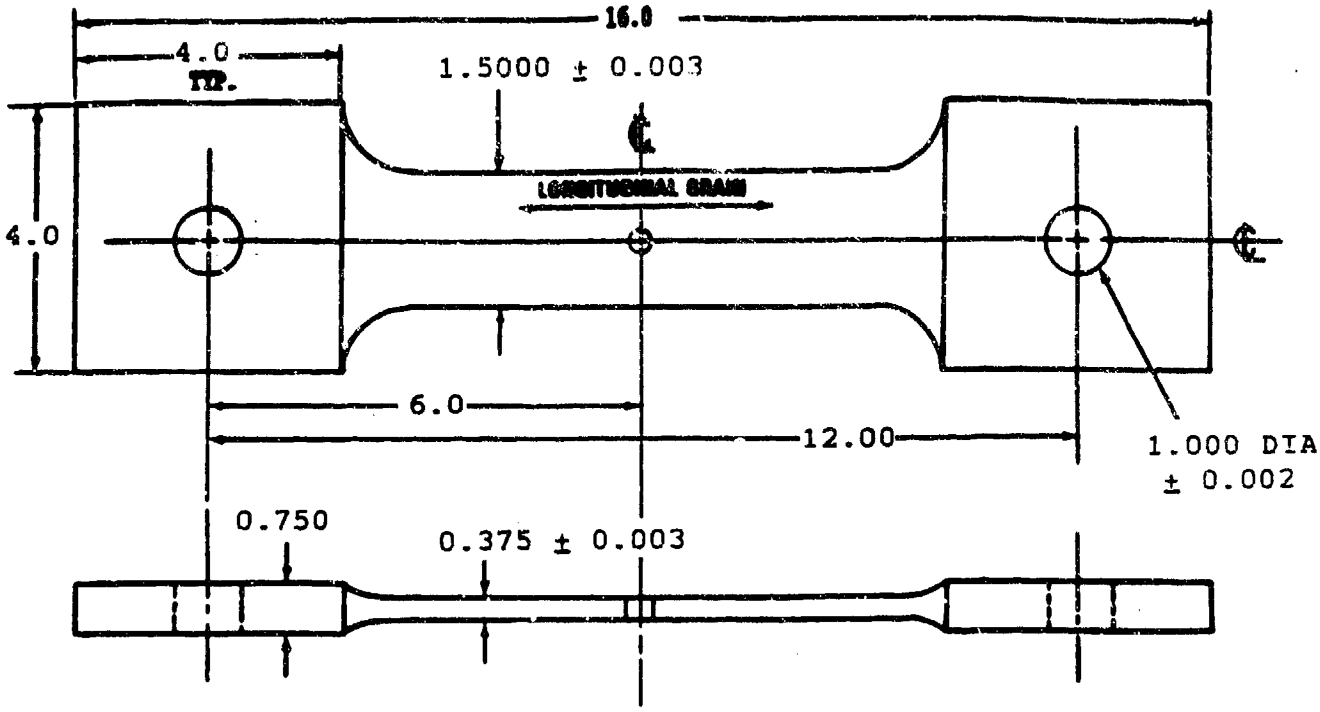


Figure 16. Dog-Bone Specimen with 1.5" Width.

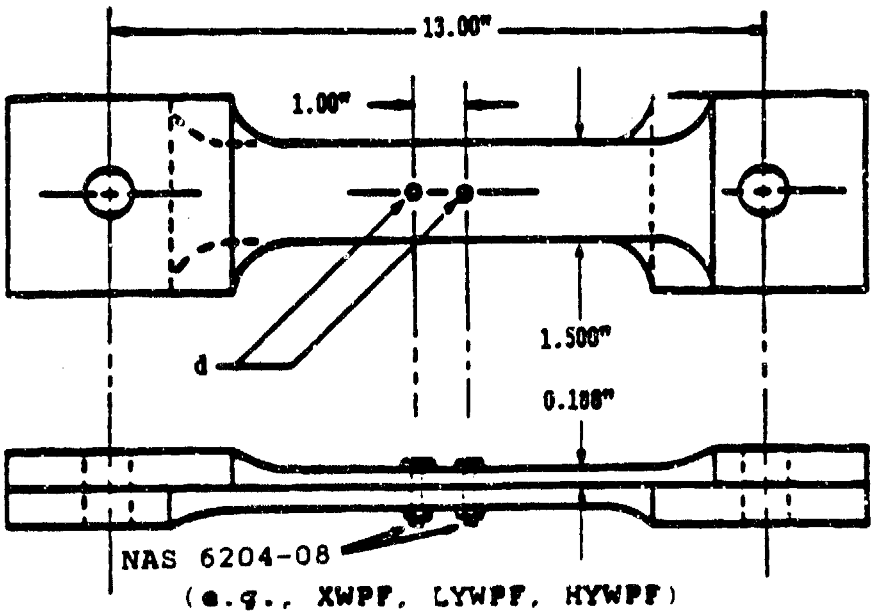


Figure 17. Double-Reversed Dog-Bone Specimen with 1.5" Width.

given crack size were made for data sets other than WPF and XWPF. Fractographic results for the third data set "WWPF" from Volume III [6] will be used to correlate with the durability analysis predictions.

Specimen design details for WWPF data set are shown in Fig. 5 (same as WPF data set), except that the specimen is wider (i.e., 3" width). Such specimens are wide enough to provide fractographic data in the large crack size region. Specimens for the WWPF data set were fatigue tested to failure using the same load spectrum (F-16 400 hour) and maximum peak (gross) stress level (i.e., 34 ksi) as the "WPF" data set.

The prediction of crack exceedance probability, $p(i, \tau)$, for WWPF data set at service time τ = 18,400 flight hours is shown in Fig. 18 as a solid curve. Also shown in this figure are solid circles representing the actual fractographic results. Figure 18 indicates that the correlation between the durability analysis prediction and experimental results is quite reasonable.

4.2 DEMONSTRATION FOR THE F-16 LOWER WING SKINS

The two-segment DCGA-SCGA will be demonstrated using tear-down inspections results for the F-16 lower wing skins from the durability test article [25]. Fractographic results are available for the lower wing skins from the full-scale F-16 durability test article that was fatigue tested under spectrum loading to 16000 flight hours. The wing skins are 7475-T7351 aluminum and include countersunk fasteners (i.e., MS 90353-08 blind pull-through rivets) of the same type used in the test specimens of Figs. 4 and 6. The durability analysis demonstration was conducted as follows.

1. The wing skin was divided into ten stress regions as shown in Fig. 19. The stress levels and number of fastener

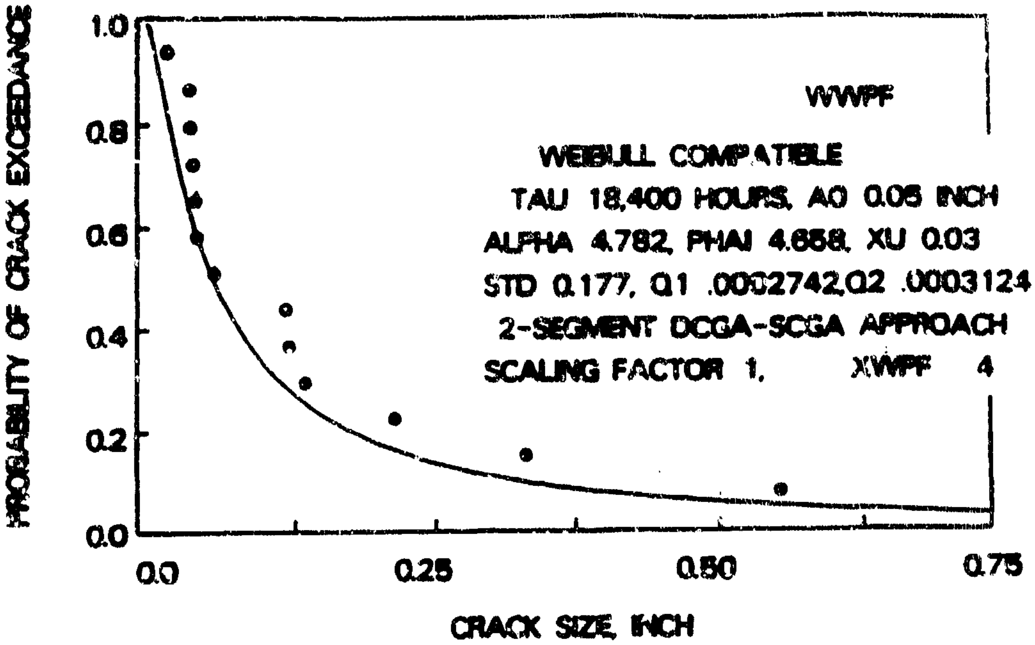


Figure 18. Correlation Between Predicted Crack Exceedance Probability Based on the DCGA-SCGA at τ = 16000 Flight Hours for WWPF Data Set and Actual Fractographic Results.

holes are shown in Table 5. Service crack growth parameters Q_1 and Q_2 for the small and large crack size regions were estimated for each of the ten stress regions. This is accomplished using crack growth rate parameters obtained from fractographic results for 1.50" wide specimen data sets (i.e., AFXLR4, AFXMR4 and AFXHR4) and two wide specimen data sets (i.e., WAFXMR4 and WAFXHR4), along with an empirical model for crack growth rate parameters proposed by Yang and Manning [3,5].

2. The EIFSD parameters obtained in Section 4.1 for countersunk fastener holes were used for F-16 fastener holes, i.e., x_u = 0.03", α = 1.716 and ϕ = 6.308. Note that these EIFS distribution parameters were determined using three narrow width specimen data sets, AFXLR4, AFXMR4 and AFXHR4.

3. Based on the DCGA-SCGA, the predictions for crack exceedance probability, $p(i,\tau)$, at τ = 16000 flight hours in ten stress regions (i.e., i = 1,2,...10) for five different crack sizes (i.e., x_1 = 0.03", 0.05", 0.1", 0.2" and 0.3") are shown in Table 6. The analysis for the DCGA-SCGA was conducted using σ_z = 0.3 (natural log basis), which is quite reasonable for countersunk fastener holes in 7475-T7351 aluminum [5,18,30]. The average number of fastener holes with a crack size greater than x_1, $\bar{N}(i,\tau)$ equal to $N_i p(i,\tau)$, at τ= 16000 flight hours are predicted for each of the ten stress regions as shown in Table 6. Predictions for the average number of fastener holes in the lower wing skin with a crack size $\geq x_1$ at 16000 flight hours, $\bar{L}(\tau)$, and its standard deviation $\sigma_L(\tau)$, are shown in Table 6 for five crack sizes. $\sigma_L(\tau)$ values are based on the Binomial distribution. Using $\bar{L}(\tau)$ and $\sigma_L(\tau)$, the extent of damage for any crack size can be estimated for selected probabilities. Theoretical predictions shown in Table 5 are plotted in Fig. 20. Results based on the DCGA-DCGA [5] and the DCGA-SCGA are plotted in Fig. 20

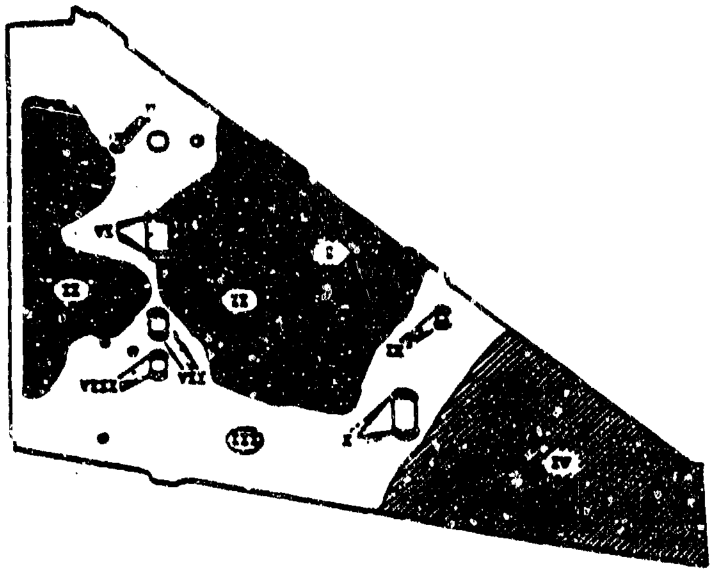


Figure 19. Stress Regions for Fighter Lower Wing Skin.

Table 3. Stress Levels and Number of Fastener Holes for Fighter Lower Wing Skin.

STRESS REGION	MAX. STRESS LEVEL, σ_i (ksi)	NO. OF FASTENER HOLES N_i
I	28.3	59
II	27.0	320
III	24.3	680
IV	16.7	469
V	28.4	8
VI	29.2	30
VII	32.4	8
VIII	26.2	8
IX	26.2	12
X	25.7	20
		1614

Table 5. Durability Analysis Results for Fighter Lower Wing Skin Based on DCGA-SCGA ($\mathcal{T}$ = 16000 Flt. Hrs.).

STRESS REGION	NO. HOLES N_i	MAX. STRESS σ_i(ksi)	x_1 = 0.03"		x_1 = 0.05"		x_1 = 0.1"		x_1 = 0.2"		x_1 = 0.3"	
			$p(i,\mathcal{T})$	$\bar{N}(i,\mathcal{T})$	$p(i,\mathcal{T})$	$\bar{N}(i,\mathcal{T})$	$p(i,\mathcal{T})$	$\bar{N}(i,\mathcal{T})$	$p(i,\mathcal{T})$	$\bar{N}(i,\mathcal{T})$	$p(i,\mathcal{T})$	$\bar{N}(i,\mathcal{T})$
1	59	28.3	.0739	4.36	.035	2.07	.0183	1.08	.0071	.42	.00348	.20
2	320	27.0	.0449	14.37	.0145	4.64	.00566	1.81	.00126	.40	.000419	.13
3	680	24.3	.0144	9.79	.0000683	.05	.0000066	.004	.0000066	.004	.0000066	.004
4	469	16.7	.000239	.11	.00	.00	.0000066	.003	.0000066	.003	.0000066	.003
5	8	28.4	.0760	.61	.0371	.29	.0196	.16	.00783	.06	.00392	.03
6	30	39.2	.103	3.09	.0577	1.73	.0335	1.00	.0158	.47	.00894	.27
7	8	32.4	.287	2.29	.225	1.80	.16	1.25	.104	.83	.0756	.60
8	8	26.2	.0326	.26	.00714	.06	.00187	.01	.000196	.002	.0000451	.00
9	12	26.2	.0326	.39	.00714	.09	.00187	.02	.000196	.002	.0000451	.00
10	20	25.7	.0264	.53	.00403	.08	.000621	.01	.000031	.001	.0000096	.00
	1614			35.80		10.81		5.377		2.192		1.237

x_i (In.)	$\bar{L}(\mathcal{T})$	$\sigma_L(\mathcal{T})$	AVERAGE EXPERIMENTAL RESULTS
.03	35.80	5.800	14.5
.05	10.81	3.185	9.5
.1	5.38	2.262	7.0
.2	2.19	1.451	2.0
.3	1.24	1.097	.5

$$\bar{L}(\mathcal{T}) = \sum_{i=1}^{m} \bar{N}(i,\mathcal{T})$$

$$\sigma_L(\mathcal{T}) = \left\{ \sum_{i=1}^{m} N_i\, p(i,\mathcal{T})[1-p(i,\mathcal{T})] \right\}^{1/2}$$

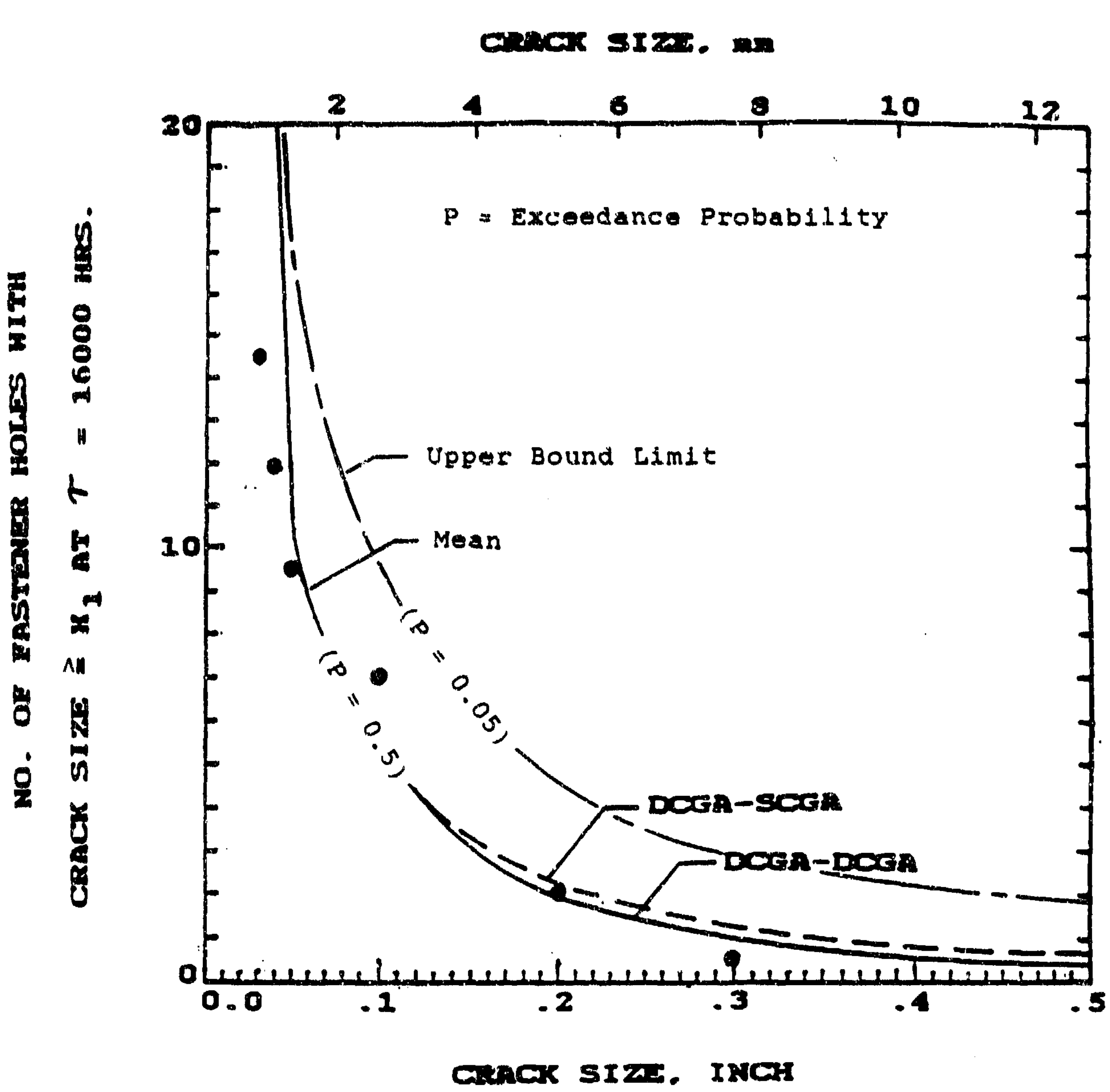


Figure 20. <u>Correlations between Theoretical Predictions and Experimental Results for Fighter Lower Wing Skin for Extent of Damage at τ = 16000 Flight Hours.</u>

as a solid curve and dashed curve, respectively. The results are identical for both approaches for $x_l \leq a$ (0.05"). Fighter lower wing skin tear-down inspection results are shown in Table 6 and they are plotted in Fig. 20 as solid circles. The extent of damage, based on the DCGA-SCGA, was estimated for an exceedance probability of P = 0.05 from $\bar{L}(\tau) + 1.65\sigma_L(\tau)$ using the $\bar{L}(\tau)$ and $\sigma_L(\tau)$ values shown in Table 6. Results are plotted in Fig. 20 as a solid-dashed-solid curve (— – —).

Durability analysis predictions for the lower wing skin, based on the DCGA-SCGA and the DCGA-DCGA, correlate well with the tear-down inspection results. Both approaches are considered reasonable for evaluating functional impairment due to fuel leakage/ligament breakage in metallic aircraft structures. However, the DCGA-SCGA is recommended for durability analysis because predictions are more accurate and slightly more conservative than those based on the DCGA-DCGA. Extensive demonstrations for the DCGA-DCGA and the DCGA-SCGA are given in Volume II [5].

It has been shown that coupon specimens can be used to establish the initial fatigue quality of fastener holes for full-scale aircraft structure. The predicted probability of crack exceedance can be used to estimate statistically the "extent of damage" for a durability-critical component for selected exceedance probabilities. This type of information provides a physical description of the state of damage for a durability-critical component and a logical basis for estimating structural maintenance/repair requirements and costs.

The stress level in each stress region is important for crack growth predictions. Therefore, the stress analysis for durability-critical components should reflect appropriate finite element grid sizes to obtain the stress analysis accuracy desired for each stress region.

SECTION V

RECOMMENDED CHANGES TO AIR FORCE DURABILITY DESIGN REQUIREMENTS AND PHILOSOPHY

Proposed changes in current Air Force durability design requirements [1,2] and philosophy are recommended and discussed in this section. The following changes in current durability design philosophy and requirements for metallic airframes are recommended:

1. Initial fatigue quality (IFQ) should not be represented by the same initial flaw size irrespective of material, type of fastener hole, structural details, manufacturing processes, etc. For example, a larger initial flaw size should be assumed for a countersunk hole than for a straight-bore hole for clearance-fit fasteners in the same material in which the holes were drilled using comparable methods. Fatigue test results for 7475-T7351 aluminum from the current program and two other programs [24,25] justify this recommendation. Furthermore, we have observed during the course of this program that an initial flaw size of .01" radius corner flaw may not be large enough for clearance-fit fastener holes for a deterministic-based durability analysis. Although MIL-A-87221 allows initial flaw sizes >.01" to be used for durability analysis, there is no motivation for contractors to do so.

2. An equivalent initial flaw size distribution (EIFSD) should be used to represent the initial fatigue quality of structural details. Equivalent initial flaws, based on the back-extrapolation of fractographic results, should be treated as a random variable. Then, the effects of scatter due to material, type of structural detail, design concept and manufacturing process on initial fatigue quality can be more properly accounted for. With a fixed initial flaw size requirement there is no way to discriminate the effects of material, structural detail and manufacturing process on initial fatigue quality. Methods for defining EIFSs and the EIFSD should be standardized and guidelines provided so that IFQ will be consistently defined and utilized for durability analyses. The IFQ methods and guidelines developed under this program should be adopted.

3. The test plan for the Aircraft Structural Integrity Program (ASIP) should incorporate requirements for an initial fatigue quality (IFQ) data base. Such a data base can be economically and timely acquired as a part of the normal ASIP effort. For example, by not preflawing structural details in selected test specimens, "natural fatigue crack" data can be obtained - thereby satisfying data requirements for IFQ, dur-

ability and damage tolerance. Some additional testing and fractography may be required, beyond the normal ASIP effort, depending on the desired confidence level and circumstances. In any case, if IFQ data requirements are incorporated into the ASIP test plan, then such data can be acquired with a minimum impact on cost and schedule.

4. The probabilistic durability analysis method developed under this program is a "durability design tool." It complements the current deterministic durability analysis approach and it provides a powerful decision-making tool for analytically quantifying structural durability and evaluating durability design tradeoffs.

5. In MIL-A-87221, Section 3.11 (pg. 375) it is stated that..."Durability must be designed into the structure to maximize the eventual life of the airframe." However, current deterministic-based durability analysis methods, based on a single initial flaw size in the worst case detail in a group of details, do not provide quantitative information for assessing excessive cracking or probability of functional impairment. The following "quantitative information" should be predicted at a selected service time following the full-scale durability verification test: (1) extent of damage (i.e., how many structural details are expected to exceed the limiting crack sizes associated with functional impairment), (2) probability of crack exceedance (i.e., probability of exceeding functional impairment crack size limits), and (3) probability of functional impairment (i.e., a quantitative measure of the risk of functional impairment). A quantitative durability analysis is very attractive for incorporating durability into the design process. The results of the full-scale durability test and the quantitative durability analysis should be used to evaluate appropriate final durability design trade-offs and production modifications.

5. A distinction should be made between "initial quality" and "initial fatigue quality" as follows. Initial quality is a physical description of the actual initial flaws in a structural detail that can be determined by NDI or other suitable means. Initial fatigue quality describes the EIFSD based on the back-extrapolation of suitable fractographic results. As such, an EIFSD is artificial, and cannot be verified by NDI.

6. The following terms should be added to the list of definitions in MIL-A-8866B[1] and MIL-A-87221 [2]: (1) equivalent initial flaw size, (2) initial fatigue quality, (3) extent of damage, (4) probability of crack exceedance, (5) probability of functional impairment, and (6) equivalent initial flaw size distribution. These terms are defined elsewhere [e.g., 4,18].

The proposed changes in durability analysis philosophy and requirements would have a significant impact on the following: schedule, cost, personnel, training, testing, data base, analysis, evaluation and practices. It would take time for engineers and contractors to become familiar with the probabilistic durability analysis approach. However, the aerospace industry had to do the same thing when damage tolerance and durability requirements were first introduced. There are many potential pay-offs for adopting the recommendations in this section, including: (1) improved airframe durability/life prediction capability, (2) reduced maintainability/supportability requirements, (3) providing useful information for fleet manager to evaluate usage options, trade-offs and risks, (4) lower life-cycle-costs, (5) increased confidence in the product, and (6) provide a useful tool for achieving "Reliability and Maintainability 2000" goals.

SECTION VI

DURABILITY ANALYSIS SOFTWARE

Software is available for implementing the advanced durability analysis method described in Section II of this Volume (IV) and in Volume I [4]. A comprehensive software user's guide is given in Volume V [8].

6.1 SOFTWARE DESCRIPTION

The advanced durability analysis software includes six programs in "GWBASIC". The purpose of each program is described in Table 7. All programs can be implemented on an IBM or IBM-compatible personal computer.

Software is available for plotting the fractographic data for any crack size or time range and/or durability analysis results for $F_T(t)$, $p(i,\tau)$ or $F_{a(t)}(x)$. A plotting capability is available for the following durability analysis options: (1) DCGA, (2) DCGA-DCGA and (3) DCGA-SCGA. Plots can be obtained with or without correlating data. Typical example plots are shown in Fig. 21.

6.2 SYSTEM REQUIREMENTS

The advanced durability analysis software is programmed in "GWBASIC" runs on the IBM PC and compatible systems with the following minimum configuration:

Memory:	640K RAM
Operating System:	MS-DOS Version 2.0 or Later
Graphics Monitor:	Monochrome or Color
Disk Drive:	1 Double Sided Disk Drive
Printer:	IBM or Compatible Graphics Printer
Graphics Program:	Need Special "GRAPHICS" Program for Doing Screen Prints of Graphic Display

Table 7. Description of Durability Analysis Software.

PROGRAM FILENAME	PURPOSE
"FRACT"	Save or read/print out fractographic data on 5 1/4" floppy disk
"SCREEN"	Study the character and quality of a fractographic data set (tabulate data and plot fractography)
"QSZAT"	Compute pooled Q and σ_z for a given fractographic data set
"WCIFQ"	Estimate EIFSD parameters for Weibull compatible distribution function
"PLOT"	Plot fractographic data and/or durability analysis results
"ANAL"	Make durability analysis predictions

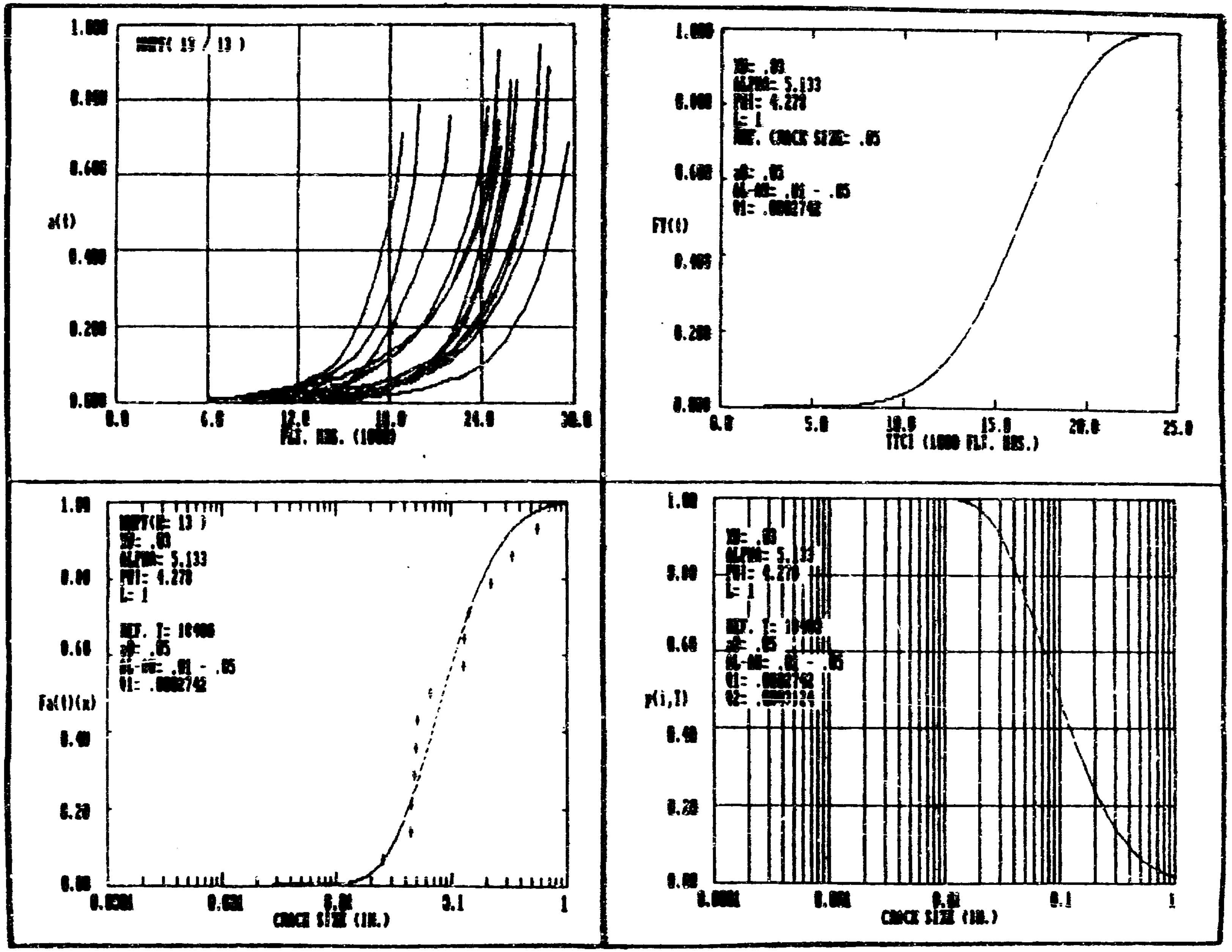


Figure 21. Example Plots for Durability Analysis Software "PLOT".

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

1. A comprehensive probabilistic durability analysis approach has been developed. It applies to the crack growth accumulation in any type of structural detail (e.g., fastener holes, cutouts, fillets, etc.). The approach has been verified for clearance-fit fastener holes in 7475-T7351 aluminum at two levels: (1) coupon specimens and (2) full-scale aircraft structure. Very reasonable durability analysis results have been obtained using the probabilistic approach, including both small cracks (e.g., $\gtrsim$ 0.05") and large through-the-thickness cracks (e.g., $\gtrsim$ 0.5").

2. It has been shown that the initial fatigue quality (IFQ) of clearance-fit fastener holes can be reasonably estimated using fractographic results from coupon specimens and that the IFQ can be represented by an equivalent initial flaw size distribution (EIFSD). Furthermore, it has been demonstrated that the IFQ of fastener holes in full-scale structures can be defined using coupon specimens.

3. The probabilistic durability analysis approach developed can be used to "quantify" structural durability in meaningful terms such as: (1) probability of crack exceedance at any service time, (2) probability of functional impairment at any service time, (3) cumulative distribution of service time to reach any given crack size, (4) extent of damage, and (5) structural wearout rate. Since the probabilistic approach developed accounts for the fatigue crack growth accumulation in each structural detail susceptible to fatigue cracking in service, it is referred to as a "quantitative durability analysis approach." The extent of damage prediction at a given service time is defined by the statistics, such as the average and standard deviation of the number of structural details expected to exceed functional impairment crack size limits. This quantitative prediction provides an effective basis for evaluating functional impairment, economic life and structural wearout, and trade-offs as a function of the design and service variables.

4. The probabilistic durability analysis approach is a powerful "durability design tool." It gives the user new durability analysis capabilities and features not provided by the existing deterministic crack growth approach based on the "worst case" detail within a group of details. The probabilistic durability analysis method is not intended to completely replace the deterministic crack growth approach in the durability design process. The deterministic crack growth approach will continue to be a valuable tool for durability

analysis - primarily during the preliminary design process. Since a deterministic crack growth analysis provides information only for the "worst case" detail within a group of details, it cannot provide the "extent of damage" type information for the entire population of structural details.

5. Equivalent initial flaw sizes (EIFSs) are determined by back-extrapolating fractographic results. Since the fractographic data depends on the testing conditions (e.g., stress levels, load spectrum, % bolt load transfer, etc.), EIFSs are not strictly "generic." However, EIFSD parameters can be estimated for different fractographic data sets using the data pooling and statistical scaling procedures. It has been conclusively shown that the EIFSD based on given fractographic data sets can be used to obtain very reasonable durability analysis predictions for the other data sets and full-scale aircraft structure for clearance-fit fastener holes (both straight-bore and countersunk) in 7475-T7351 aluminum. It should be clear that an EIFSD does not necessarily contain the "rogue flaw."

6. When an EIFSD is grown forward to a selected service time, the service crack growth should be consistent with the "basis" for the EIFSs. Therefore, the analytical crack growth program used [e.g., 16,17] should be "tuned" or "curve fitted" to the EIFS master curves reflected in the EIFSD.

7. Probabilistic-based durability analysis methods [4, 5,18] are now sufficiently developed and demonstrated for immediate applications to metallic airframes. An updated durability design handbook and software for an IBM or IBM-compatible PC are available for implementing the advanced durability analysis.

8. A "natural fatigue crack" data base for estimating the initial fatigue quality of structural details can be acquired as a part of the Aircraft Structural Integrity Program (ASIP) test plan. For example, by not preflawing structural details in test specimens, "natural fatigue crack" data can be obtained--thereby satisfying data requirements for both durability and damage tolerance. Additional testing and fractographic evaluations, beyond the normal ASIP effort, may be needed to define IFQ, depending on the desired confidence level and circumstances. IFQ data requirements can be readily incorporated into the ASIP test plan to minimize the cost and time for acquiring the requisite data base.

9. The stress level for each stress region is important for crack growth predictions. Therefore, the stress analysis for durability-critical components should reflect appropriate finite element grid sizes to obtain the desired stress analysis accuracy for each stress region.

10. Probabilistic durability analysis methodologies developed can be extended to establish the optimal inspection/repair/replacement/proof test maintenance for life management of metallic aircraft structure. The extension can be made based on some fundamental research efforts appearing in the literature [e.g., 31-42].

7.2 RECOMMENDATIONS

1. The advanced durability analysis method developed under this program should be used for future durability analyses for metallic airframes. Structural durability can now be quantitatively accounted for in the durability design process.

2. Recommendations for durability analysis are as follows: (1) define the equivalent initial flaw size distribution (EIFSD) using fractographic data in the small crack size region (e.g., 0.01"-0.05"), (2) use fractographic data pooling procedure and statistical scaling technique to estimate the EIFSD parameters in a "global sense" for a "single hole population" basis, and (3) use the two-segment deterministic-stochastic crack growth approach (DCGA-SCGA) to predict the extent of damage in the entire durability critical component; the two-segment deterministic crack growth approach (DCGA-DCGA) is also reasonable but it is slightly less conservative than the DCGA-SCGA.

3. The recommended changes in Air Force philosophy and durability design requirements described in Section V of this volume should be adopted. This will allow the full potential of the probabilistic durability analysis approach to be utilized in the design and analysis of future metallic aircraft structures.

4. The advanced durability analysis approach developed under this program should be investigated for other structural details and considerations. For example, the life enhancement effects of fastener hole cold working, interference fit fasteners, press fit bushings, etc., on initial fatigue quality should be investigated. Similarly, the initial fatigue quality of structural details, such as cutouts, lugs, fillets, etc., should be investigated. Suitable test specimens should be developed and standardized for acquiring initial fatigue quality data for the key structural details to be included in the durability analysis.

5. Future ASIP test plans should be designed to provide data for initial fatigue quality, durability and damage tolerance. Selected fatigue tests should be conducted using specimens without intentional preflaws so that "natural fatigue crack" data can be obtained. This approach should be used to minimize cost and time for acquiring the requisite IFQ data base.

6. The meaning and limitations of EIFSs and an EIFSD must be emphasized. In particular, all EIFSs should be grown forward consistent with the basis for the EIFSD. The EIFSD should not be grown forward using an analytical crack growth program without tuning and considering the basis for the EIFS.

7. All aerospace contractors should use the same method to define EIFSs for different materials and structural details so that compatible EIFSs can be obtained. The "Qa(t) model" [4,5] is reasonable for determining EIFSs. This model or some other suitable model should be used to standardize the way EIFSs are determined. Then, for a given fractographic data set, fractographic crack size range (AL - AU) and the same analysis procedure, all contractors will obtain the same EIFSs. By standardizing the way EIFSs are determined, EIFSs from various sources can be directly compared--thereby providing a means for cataloging and utilizing existing data from various sources to estimate the initial fatigue quality of structural details.

8. Initial fatigue quality should not be represented by the identical initial flaw size distribution irrespective of material, type of fastener hole, structural details, manufacturing processes, etc. For example, the statistical dispersion of EIFSD for countersunk holes is significantly larger than that of the EIFSD for straight-bore holes for clearance-fit fasteners in the same material in which the holes were drilled using comparable methods. Thus, if a single initial flaw size is selected for a given probability or percentile (e.g., 1/1000), and the deterministic approach is used for durability analysis, the initial flaw size for a countersunk fastener hole should be larger than that for a straight-bore fastener hole based on our investigation.

9. The probabilistic durability analysis approach should be investigated for discriminating "quality" at three levels: (1) material, (2) manufactured detail, and (3) component. Of particular interest is the following question: "How does improvement in initial material quality translate into improvement in life of actual aircraft components?" This research can be built on the advancements made under this program and the work conducted by ALCOA [e.g., 27,28].

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ACRONYMS

ADA	=	Advanced Durability Analysis
ASIP	=	Aircraft Structural Integrity Program
CLSSA	=	Combined Least Square Sums Approach
DADTA	=	Durability and Damage Tolerance Assessment
DCGA	=	Deterministic Crack Growth Approach
EIFS	=	Equivalent Initial Flaw Size
EIFSD	=	Equivalent Initial Flaw Size Distribution
FHQ	=	Fastener Hole Quality
HEIFS	=	Homogeneous EIFS
IFQ	=	Initial Fatigue Quality
LEFM	=	Linear Elastic Fracture Mechanics
LT	=	Load Transfer Through the Fastener
MM	=	Method of Moments
NDE	=	Non Destructive Evaluation
NDI	=	Non Destructive Inspection
NLT	=	No Load Transfer Through the Fastener
SCGA	=	Stochastic Crack Growth Approach
SCGMC	=	Service crack growth master curve
SSE	=	Sum Squared Error
TSE	=	Total Standard Error
TTCI	=	Time-to-Crack Initiation